HISTORICAL ECOSYSTEM MODELLING OF THE UPPER GULF OF CALIFORNIA (MEXICO): FOLLOWING 50 YEARS OF CHANGE.

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Abstract

Ecological conditions in the upper Gulf of California (Northwest Mexico) have deteriorated significantly over the past seventy years through the removal of nutrients and freshwater from the Colorado River. Acting at the same time, uncontrolled exploitation has brought at least three fisheries to collapse and several endemic species, such as giant Gulf croaker (*Totoaba macdonaldi*) and the vaquita porpoise (*Phocoena sinus*), near to extinction. This motivated a study to quantify the ecological impacts attributable to diversion of the Colorado River on the dynamics and interactions of the upper Gulf of California (UGC). In the absence of baseline studies for the pre-diversion period, this work has combined scientific information, newly-gathered local knowledge from fishers (LFK), and information from industrial and artisanal fisheries to reconstruct for the first time models of the upper Gulf of California for three key periods: 1950, 1980 and 2000. Reconstruction of these past ecosystem states are based on mass-balanced models (130 species considered in 50 functional groups) generated using the Ecopath and Ecosim approach and software. Dynamic simulations, with ecosystem model parameters fitted to all known biomass and fisheries data (historical time-series of catch-at-age data and biomass surveys since 1970s reported by the Institute of National Fisheries, Mexico), were used to track and emulate changes caused by water diversion and fishing within the limits set by fluctuations in climate such as the El Niño events of 1983, 1993 and 1997. The UGC is an ecosystem to be highly-dependent on detritus-benthic components. Biomasses appear to be largely controlled by lower trophic levels. A highly diverse artisanal fishery targeting a wide range of species, impacts all levels of the food web. These effects need to be taken into account to be considered in the management plans in the region. During the last five decades, change in trophic level indicated important impacts of fishing, resulting in an average decline in the trophic level of 0.02 trophic level/decade. Also, there was a notable loss in the abundance of detritivores during the last 50 years, with a reduction of 64% in the total estimated biomass of all the groups located in trophic level 2 and 2.5. This loss is affecting the incorporation of organic matter to higher trophic levels of the food web, a critical function in any ecosystem. Overall, numerous changes in the energy flows and production rates were estimated during the research, indicating a large reduction in the energy and dynamics of the upper Gulf. These changes affect the structure and function of this ecosystem, limiting its ability to recover from future natural or human forces. Simulations suggested that river flows of only 1% of the undepleted level may produce increases of around 10% in the total biomass of the UGC, reflecting the enormous role of the Colorado River in the productivity in the region. This is particularly important considering that this region provides 10% of the annual Mexican landings (INEGI, 2001), and provides a preliminary accounting of the ecological and economic losses for Mexico during the last five decades since American river dams were built. Simulations of the effect of reduced river flows and environmental (El Niño) influences on the UGC ecosystem revealed the superficiality of our knowledge of the quantitative process simulated in the models and reconstruction of past states of natural aquatic ecosystems like the upper Gulf of California. It is evident that any attempt to restore the UGC must be initiated with a

parallel study of the climate change in its influence in the region. This research suggested that human intervention can trigger rapid and significant changes in the structure and function of small marine ecosystems such as the upper Gulf of California. In the future, human interventions in river deltas, such as damming rivers and water abstraction, must be considered as one of the major forces affecting the steady state evolution of these ecosystems, impacting their natural processes, productivity, biodiversity and the human communities that depend on them for food, work and culture.

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Chapter I.

Overview and Summary.

1.1. Need and motivation for modelling the upper Gulf of California.

Despite the fact that the Gulf of California is the world's youngest sea, created when the San Andres faults split the Northwest of Mexico and allowed the Pacific to flow in, it is recognized as one of the most productive marine ecosystems in the world. Furthermore, its richness produces 40% of Mexico's total landings and it provides jobs to nearly 30,000 fishermen (INEGI, 2001). A critical and unique area of this large marine ecosystem is its northernmost region, the upper Gulf of California (UGC), including one of the world's great desert deltas, the Colorado River Delta (CRD). This delta provides 10% of the national landings and has supported important fisheries since 1920s. The historical richness of this area has been explained mainly by the nutrients and sediments provided by the Colorado River and by extreme tidal and upwelling processes (Carraquiry and Sánchez, 1999).

Unfortunately, the CRD/UGC exemplifies human efforts to divert and control the major rivers in the world. As in many other river deltas in the world, such as the Amazon (Barthem *et al.*, 1995) or the Mississippi (Arthington and Welcomme, 1995), the CRD has suffered a combination of river impoundment and diversions since 1905, mainly because of a series of U.S. dams and irrigation projects (1935: the completion of the huge Hoover dam; 1963: completion of Glen Canyon dam) to divert approximately 18 billion m^3/year of freshwater and up to 450 million of metric tonnes/year of sediment that once were delivered into the upper gulf (Van Andel, 1964; Carbajal *et al.*, 1997; Carraquiry and Sánchez, 1999). This anthropogenic intervention has had a devastating effect not only on the delta wetlands, but also on the estuarine and marine waters of this ecosystem (Briggs and Cornelius, 1998; Brusca *et al* 2001; Glenn *et al.*, 2001) with an evident alteration in the hydrography of the CRD/UGC system. In turn, this has produced a permanent increase of salinity from 22-35 before the dams were built and also during

controlled releases (Townsend, 1901; Lavín *et al.*, 1998; Lavín, 1999) to current salinities that are typically in the range of 35-45 (Alvarez-Borrego, 1975; Lavín, 1999). The increase in salinity in the delta and upper Gulf has fundamentally changed spawning and nursery ground conditions that are critical to hundred of species, including invertebrates, fish, reptiles, marine mammals and birds that use the delta and its marine zone (Sykes, 1937).

Several examples illustrate the importance of the freshwater, sediments and nutrients delivered by the Colorado River. The endemic population of bivalves (mainly *Mulina colorandensis*) has shown a reduction of more than 90% from pre-dam densities (Kowaleski *et al.*, 2000; Rodriguez *et al.*, 2001; Flessa *et al.*, 2001). Blue shrimp catches (*Litopenaeus stylirostris*) and their post-larva abundances are positively correlated with the previous year's discharge (Galindo-Bect and Glenn, 2000; Aragón-Noriega and Calderón-Aguilera, 2000; Calderón-Aguilera *et al.*, 2002). Finally, there is the remarkable case of the gulf corvina (*Cynoscion othonopterus*), endemic to the Gulf of California, but not been seen in the upper gulf for 40 years, but which returned in large numbers after the floods of El Niño 1992-93 (Zengel *et al.*, 1995; Cudney-Bueno and Turk, 1998). Also, important reductions of refuge habitats for more than 100,000 migratory birds visiting the area each winter have been documented (Boyer, 1996; Brusca *et al.*, 2001). These examples illustrate that the Colorado River once played a major role in not only supplying nutrients, but also providing low-salinity nursery areas for larval shrimps and fish fry where euryhaline predators could not penetrate.

Uncontrolled fisheries have brought several endemic species near to extinction. The giant Gulf Croaker (*Totoaba macdonaldi*), has the unenviable distinction of being the first marine fish listed under CITES and ESA. The vaquita porpoise (*Phocoena sinus*) is also endangered (Cisneros-Mata *et al.*, 1995; Román-Rodríguez and Hamman. 1997; Jaramillo-Legorreta, 1999; D'Agrosa *et al.*, 2000), but the role of increased salinity in their key habitats is unknown (Glenn *et al.*, 2001). Because ecological conditions in the CRD/UGC have deteriorated significantly over the past 70 years, resulting in an

economic and ecological crisis during the late 1980s, this region was declared a Biosphere Reserve in 1993 (Diario oficial, 1993; McGuire and Greenberg, 1993).

1.2. Research objectives.

This study aims to use an ecological theory to evaluate trophic changes in the upper Gulf over the past 50 years as a result of the elimination of nutrients by the series of dams built along the Colorado River and by the intense fishing pressure that has been imposed over the past several decades in this ecosystem. The two main objectives are: (1) to describe the ecosystem of the UGC/CRD using trophodynamic ecosystem simulation models representative of 1950, 1980 and 2000 with the help of Ecopath and Ecosim software (EwE; Christensen *et al.*, 2000); and (2) to investigate possible policy goals based on restoration of delta ecosystems that are under similar conditions as the upper Gulf or that could be used in the near future, evaluating the cost and benefits of fisheries among economic, ecological and social criteria. It is expected that this knowledge may improve the understanding of these kinds of human interventions and enable the incorporation of the results from this study into policies and monitoring programs. The following are planned tasks associated with each objective:

Objective I:

1. Review of historic landings, as reported by the Institute of National Fisheries, Mexico (INP).
2. Examination of fishing effort, discards, bycatch and fisheries value associated with these harvests.
3. Construction of mass-balanced EwE models of the UGC system representative of the 1950, 1980 and 2000 periods, covering major fluxes: phytoplankton and primary production, zooplankton and secondary production, major fish species and their fisheries, marine mammals and their food consumption.
4. To include qualitative information and knowledge from local fishermen of the

UGC (San Felipe, Golfo de Santa Clara and Puerto Peñasco) as an additional tool to estimate some parameters required by EwE for the 1950 and 1980 models.

Objective II:

1. Examination of changes in the ecosystem form and process by comparing the models constructed according to objective I. This evaluation is performed using dynamic simulations in Ecosim.
2. Generate forecasts of ecological, economic and employment responses to possible management alternatives using the EwE approach.
3. Employ dynamic Ecosim simulations using the Colorado River discharge as a forcing factor to track and emulate the effect of inter-annual climate variations such as El Niño/La Niña in the structure and function of the UGC.

1.3. Biodiversity impacts of large dams.

Major dams meet one or more of the following criteria: are at least 150 m high; have a volume of at least 15 million m^3. They have a reservoir capacity of at least 25 km^3 or a generation capacity of at least one Gigawatt (McCully, 1996). In 1998, there were 306 major dams in the world with 57 planned for the near future (Revenga *et al.*, 1998). The Colorado River has the third greatest number of major dams in the world, i.e. a total of 12 (just behind the Paraná and Colombia rivers with 14 and 13 major dams, respectively).

In general, dams and their reservoirs impact freshwater and marine biodiversities by:

1. Blocking movement of migratory species up or down rivers, causing extirpation or extinction of genetically distinct stocks or species.
2. Changing turbidity and sediment levels, trapping silt in reservoirs deprives downstream deltas and estuaries of maintenance materials and nutrients that help make them productive. This could change the normal seasonal estuarine discharges, which can reduce the supply of entrained nutrients, impacting the food chains that sustain

fisheries in estuarine deltas.

3. Changing conditions in rivers flooded by reservoirs: running water becomes still, silt is deposited and deepwater zones, temperature and oxygen conditions are changed, making the environment unsuitable for river and delta species.

In the case of estuarine and marine impacts, dams are associated with changes in seasonal flows, turbidity and productivity as in the North Caspian, where dams caused an increase in salinity from 8 to 19 (Rozengurt and Hedgepeth, 1989). The estuarine mixing zone was compressed and moved up to the delta, reducing the nutrient load (especially phosphorus) and the sediment load was reduced by as much as 5 times. In the Volga, biomass of phytoplankton, zooplankton and benthic organisms decreased by as much as 3.5 times and a substantial part of the Volga flood plains, that served as nursery grounds for many valuable fishes, was transformed into drying swamps or deserts (Rozengurt and Hedgepeth, 1989). The Volga diversion resulted in a progressive deterioration and significant decline in natural recruitment of commercial species, producing a substantial reduction from three to five times for three sturgeon species, and up to 10 times for bream (*Abramis brama*), Caspian roach (*Rutilus rutilus*) and nearly 100 times for the commercial fishery of Caspian herrings (*Alosa kessleri volgensis*). In a few extreme cases, such as the stellate sturgeon 'sevruga' *(Acipenser stellatus*), it was necessary to release fry reared in hatcheries throughout a period of 20 years in order to save this species from extirpation in this region (Rozengurt and Hedgepeth, 1989).

1.4. Present and past ecosystem models: The 'Back to the Future' policy approach.

Failure to predict fish stock collapses and their economic and ecological cascade of effects in aquatic ecosystems have resulted in severe critiques single of species fisheries science (Hutchings *et al.*, 1997; Pitcher *et al.,* 1998). It is believed that some depletions and collapses around the world are even worse than we had thought (e.g., large fish, Myers and Worm 2003; fish biomass, Christensen *et al.* 2003; whales, Roman and Palumbi 2003; sharks, Baum *et al.* 2002, Schindler *et al.* 2003: turtles, Hays *et al.* 2003).

Increasing attention has focused on the importance interdisciplinary information about past abundances in determing the extent of the collapse and the potential for restoration (Pitcher *et al.*, 2005; Sáenz-Arroyo *et al.*, 2005).

In the UGC, changes to the marine fauna (e.g., the decline of sharks, shrimps, benthic communities and a near extinction of totoaba and vaquita) are parallel to drastic changes in the terrestrial ecology of this region. The first Spanish expeditions to the Gulf of California (e.g. Francisco de Ullóa, 1523) described the upper Gulf as a lush region bordered by vast areas of riparian corridors and tidal wetlands that supported beavers, otters and thousand of birds, with deer, Cimarron rams, wolves and mountain lions. These pristine conditions seemed to persist until the twentieth century (according to the maps, flora and fauna described by Sykes, 1937 and Osorio-Tafall, 1947).

It has been suggested that the lack of communication between scientists, policy makers and the public has also contributed to failures of fisheries science to predict major collapses around the world during the last century. It is for this reason that the combination of different disciplines to examine traditional fisheries science questions could result in a new tool that may help fisheries scientists better explain the nature of stocks and marine ecosystems. In order to answer these critical questions, a new fishery policy approach was proposed in 1998 (Pitcher *et al.,* 1998a) based on a 'rebuilding' plan derived from the architecture of past ecosystems. Basically, this new methodology, called 'Back to the Future' (BTF), attempts to understand the history of ecosystems using the entire spectrum of tools and knowledge available, i.e., incorporating the help and knowledge of maritime historians, archaeologists, ecological economists, fisheries ecologists and also, decades and sometimes hundreds of years of experience of local and indigenous people. BTF provides an integrative approach to the strategic management of marine ecosystems, including new methods for describing past ecosystems that could help in development strategies for the new fisheries that could meet criteria for sustainability and responsibility (Pitcher *et al.*, 2005). Also, BTF is particularly useful when the effect of a specific perturbation (natural or anthropogenic) needs to be evaluated by comparing

the structure of this system before and after such perturbations. This was one of the main reasons why this new methodology was employed in the quantification of ecological impacts in the upper Gulf that may be attributable to the Colorado River diversion. BTF allowed the reconstruction of this ecosystem (1950s model) for a specific period before the completion and filling of the Glenn Canyon Dam in 1960 in order to compare its trophic structure and function with the results of 30 and 50 years later (1980s and 2000s models). Changes which resulted in the system due to this anthropogenic intervention were then evaluated and, according to the BTF method, restored past conditions used as a guide to evaluate the costs and befits of future restoration policies.

The BTF approach applied in the upper Gulf of California project began with the construction of a present-day ecosystem simulation model (referred to as '2000s' model because it averages fisheries and abundances from 1995-2003). The structure and parameters of the balanced 2000 model were used as a framework for assembling the past models for the 1950s and 1980s models. During the construction of the two past models, data gained from archives, historical documents, archaeological information (clam fossils were used to estimate past abundances) and interviews vis-à-vis traditional environmental knowledge plus opinions from local fishers of the upper Gulf were included. Once the present and past models were mass-balanced, real time series of fishing efforts and mortalities were used to validate the dynamic simulations of these models. Also, by using a time series of the biomass for two main species exploited in the region in the last 60 years (shrimps, *Peneaus stylirostris, P. californiensis* and totoaba, *Totoaba macdonaldi*), it was possible to tune the three models (see details in chapter III) and to evaluate the changes in the trophic structure and function of the upper Gulf of California from 1950 to 2000. An exploratory search for sustainable fisheries was then conducted to examine tradeoffs between conservation and fishing that might help in the understanding of this ecosystem and contribute to future decisions among all the stakeholders. Finally, it was possible to challenge the present and past models with forcing functions such as the Colorado River discharge in order to emulate the effects of climate change in the upper Gulf, a critical element to consider in the modelling of past ecosystems.

1.5. Considering the effect of climate change in the modelling the past and present of the upper Gulf of California.

The UGC is a tidal shallow sea, with approximately 70 % of its area less than 200 m, and therefore it responds rather quickly to meteorological variability (Reyes and Lavín, 1997). This area is surrounded by deserts and is characterized by atmospheric and marine isolation. Mountain ridges on both sides of the gulf create an upper gulf climate that is more Mediterranean than marine (Leal and Lavín, 1999). For these reasons, El Niño/Southern Oscillation (ENSO) events have marked effects on both the physical and biological components of the upper Gulf. In the first case, Alvarez-Borrego and Schwartzlose (1979) documented a stronger invasion of Tropical Pacific water masses into the Gulf during the 1957 El Niño. Baumgartner and Christensen (1985) concluded that the principal source of inter-annual variability in the sea level climate of the Gulf of California is the changing intensity of the equatorial circulation associated with ENSO phenomena. The biological impacts of climate change in the Gulf can be evaluated at different levels; in the case of inter-annual ENSO events, some results from Valdez-Holguin and Lara-Lara (1987) suggested an increase in phytoplankton biomass during the ENSO 1982. Baumgartner *et al.* (1985) have shown that siliceous phytoplankton assemblages preserved in the laminated sediments of the anoxic Guaymas basin (Central Gulf of California) are correlated to inter-annual sea-level anomalies. They have also reported that the ENSO periods are generally marked by increases in preserved abundances of total siliceous assemblages and, in particular, by a greater number of individuals from species whose distributions are limited to tropical and subtropical waters. Also, the ENSO 1982-1983 was detected in the Gulf of California by a change in the habitual distribution patterns of silicoflagellates (small size phytoplankters with a siliceous framework), where the incursion of 'hot' waters (and tropical species) caused the decline of the silicoflagellate population in the southern part of the Gulf, and inhibited the influence of 'cold' waters of the Gulf (Pérez-Cruz and Molina-Cruz, 1988).

In general, environmental factors have a stronger impact on short-lived species, such as crustaceans and small pelagic fishes. López-Martínez *et al.* (2003) evaluated the inter-annual variation in the growth of brown shrimp (*Farfantepenaeus californiensis*) in the Gulf of California. They established a relationship between temperature and growth of the brown shrimp (optimum temperature for growth was 25°C), and concluded that growth was favorable only during moderate the ENSO events (1986 and 1992), whereas during more intense events (1982-1983), had adverse effects on growth.

These examples of the effect of climate change on the physical and biotic elements of the Gulf of California reflect the need to consider the role of climate change component in the Ecosim scenarios. It is worth noticing that the EwE approach can account for population parameters such as natural mortality, growth and recruitment, all of which are affected by inter-annual climate changes.

1.6. Previous Research.

An Ecopath model of the north region of the Gulf of California (the northern Gulf of California and the upper Gulf of California cannot be considered synonymous since their physical, chemical oceanographic conditions are different) was constructed by Morales-Zárate (2001). This Ecopath model represents the main biomass flows in this system with special emphasis on the dynamics of blue shrimp, *Liptopeneaus stylirostris,* (80% of the total shrimp catch). The model structure consisted of 29 functional groups distributed in an area of 7,172 km^2, from the Colorado Delta southward to the large islands of Tiburón and Angel de la Guarda. The average depth of the area used in this model was 200 m. Intriguingly, the most affected groups were impacted more by predation and competition than by fishing pressure. The model constructed by Morales-Zárate (2001) and Morales-Zárate *et al.* (2004) is the only relevant point of comparison for future results from my own upper Gulf model.

1.7. Thesis structure.

Chapter II presents an exploratory analysis of illegal and unreported catches in the region to estimate the total extractions to be included in the present-day model. The sources of information required for building the 2000 trophic model in the upper Gulf of California and Colorado River Delta are provided. Finally, the function and structure of this ecosystem for 2000 is presented through the results from network flow analysis. A quantitative analysis of the sensitivity and uncertainties of the data employed is discussed.

A qualitative comparison between the former pristine conditions and the changing fauna of the upper Gulf before and after the water diversion is provided in Chapter III. The results from the oral inputs and opinions from interviews of the local fishers are presented. The information gathered from this analysis was partially used to build past time series of relative abundances of the fauna in the region, a critical issue for assembling the 1950s and 1980s trophic models.

Chapter IV presents the connection of the past and present models, providing the basis for quantifying changes in the structure and function for the upper Gulf from 1950 to 2000 (considering changes in biomasses, fishing mortalities and energetic flows). This chapter also incorporates the climate change influence into the tuning process for the three models.

Chapter IV illustrates how the ecological role of a single functional group can be explored through changes in the form and structure of the past states of the upper Gulf of California ecosystem and how these changes can be used as a first approach to quantify ecological impacts attributable to diversion of the Colorado River. 76 scenarios for optimal fishing strategies under economic, social, ecological and rebuilding criteria were analyzed to find optimum fishery strategies in the upper Gulf are documented. Changes in biodiversity in the region under different fishing regimens are also discussed.

Chapter VI presents the summary and concluding comments. Benefits and limitations of the 50-year modelling of the upper Gulf are discussed.

Chapter II.

A trophic model of the upper Gulf of California and Colorado River Delta.

2.1. Physical and biological characteristics.

The study area was selected because of the historical influence of the Colorado River that once flowed 70 km south from the present day mouth (Lavín and Sánchez, 1999; Flessa *et al.,* 2001). This flow affected an area of approximately 4,550 km^2 (Fig. 1). The development and evolution of the UGC and CRD have been controlled by interaction of two geological processes: (1) the Colorado River with an average sediment supply calculated as 160 x 10^6 tonnes/year (van Andel, 1964); and (2) an extensive tidal regime in the delta region considered to be amongst the largest in the world (up to 10 m), and one which has very strong tidal currents (Álvarez-Borrego, 1983; Carraquiry and Sánchez, 1999). The northern half of the UGC is very shallow, with a minimum depth of 2 m and a maximum of 30 m, while the southern half descends to 120 m (Lavín *et al.*, 1998). The climate is continental arid, with scant rainfall and low humidity (Paden, 1991). According to the non-linear shelf model (using a constant discharge of freshwater of 2000 m^3/s) published by Carbajal *et al.* (1997), the pre-dam salinity pattern (12-34) is radically different from the present salinity of ~37, with profound impact on the UGC circulation (Lavín *et al.*, 1999). The estuary circulation is now driven by the high evaporation rate in the area of 900 cm/year with only 6.8 cm of yearly mean precipitation (Carbajal *et al.* 1997; Lavín *et al.*, 1999). These changes have transformed the UGC into an inverse or negative estuary, with higher salinity toward the head and lower salinity toward the ocean (Lavín *et al.,* 1998). The saltier water formation in the upper gulf that sinks and flows southeastwards during late winter is one of the mechanisms that maintains a salt balance in the region (López, 1997). Dam projects have trapped much of the Colorado's sediment load. Historically, a charge of 160 millions t/year of sediment was delivered into the delta (van Andel, 1964), while the sediment load today is almost zero (Carraquiry and Sánchez, 1999). Strong tidal waves (up to 10 m in the mouth) have removed historically deposited

sediments, and it is likely that the dams have engendered a sediment starvation phase in the delta. Consequently, the delta is passing through an erosional phase and exports sediments to the Northern Gulf at rates similar to those of unaltered river flows prior to 1935 (van Andel, 1964; Cupul, 1994).

Despite the ecological impact caused by the construction of dams, the UGC is one of the richest marine ecosystems in the world (Cudney-Bueno and Turk, 1998). The load capacity of its food chain has been evaluated by estimating the high primary productivity reported over recent decades (Zeitzchel, 1969; Álvarez-Borrego *et al.*, 1975; Álvarez-Borrego *et al.*, 1983; Brinton *et al.*, 1986; Valdéz-Holguín and Lara-Lara. 1987; Millán-Núñez, E. 1992; Millán-Núñez *et al.* 1999; García-Pámanes and Lara-Lara, 2001). The high fertility is explained by the tidal currents, wind-driven upwelling and the plateau topography (Lavín *et al.*, 1999), resulting in numerous areas of upwelling mainly along the eastern coast of Baja California, (Argote *et al.*, 1998) with the productive potential to maintain large food chains with no freshwater input (Millán-Núñez *et al.* 1999).

2.1.1. Historical variability of fluvial discharge.

During the nineteenth century, tidal bores of up to ten meters were registered in the delta, allowing a regular commercial navigation of steamer boats to cross the delta and go up the river (Sykes, 1937). Today, the Colorado is no longer used for navigation and its discharge has been diverted by more than 20 dams and dozens of irrigation projects (Carbajal *et al.*, 1997). The completion of the two US major dams, the Hoover Dam (1935) and the Glen Canyon Dam (1960), had the most drastic impact on the amount and timing of fresh water that reached the Gulf (Lavín and Sánchez, 1999). The first documented intervention of the Colorado was in the early 1900s when a discharge of 18×10^9 m^3/year was recorded (Sykes, 1937). In 1934, when the Hoover dam started to store water in Lake Mead, the discharge decreased by 80% (2.8×10^9 m^3/year) and showed a slight recovery between 1940 and 1952. The completion of the Glen Canyon dam in the late 1960 was responsible for a 96% discharge reduction compared with the beginning of

the century (Fig. 2).

Some strong precipitation events such as the El Niño of 1983 and 1993 released more water to the Gulf (Lavín and Sánchez, 1999; Brito-Castillo *et al.*, 2002). Indeed, the rare Colorado fresh water discharge during March and April of 1993 provided an opportunity to evaluate its importance. An evident reduction of salinity was detected (contrary to the now normal inverse estuarine situation) and a dilution pattern was observed of up to 70 km from the river mouth, verifying that the hydrography of the shallow (<30m) upper Gulf is affected by the water delivered by the Colorado River (Lavín and Sánchez, 1999).

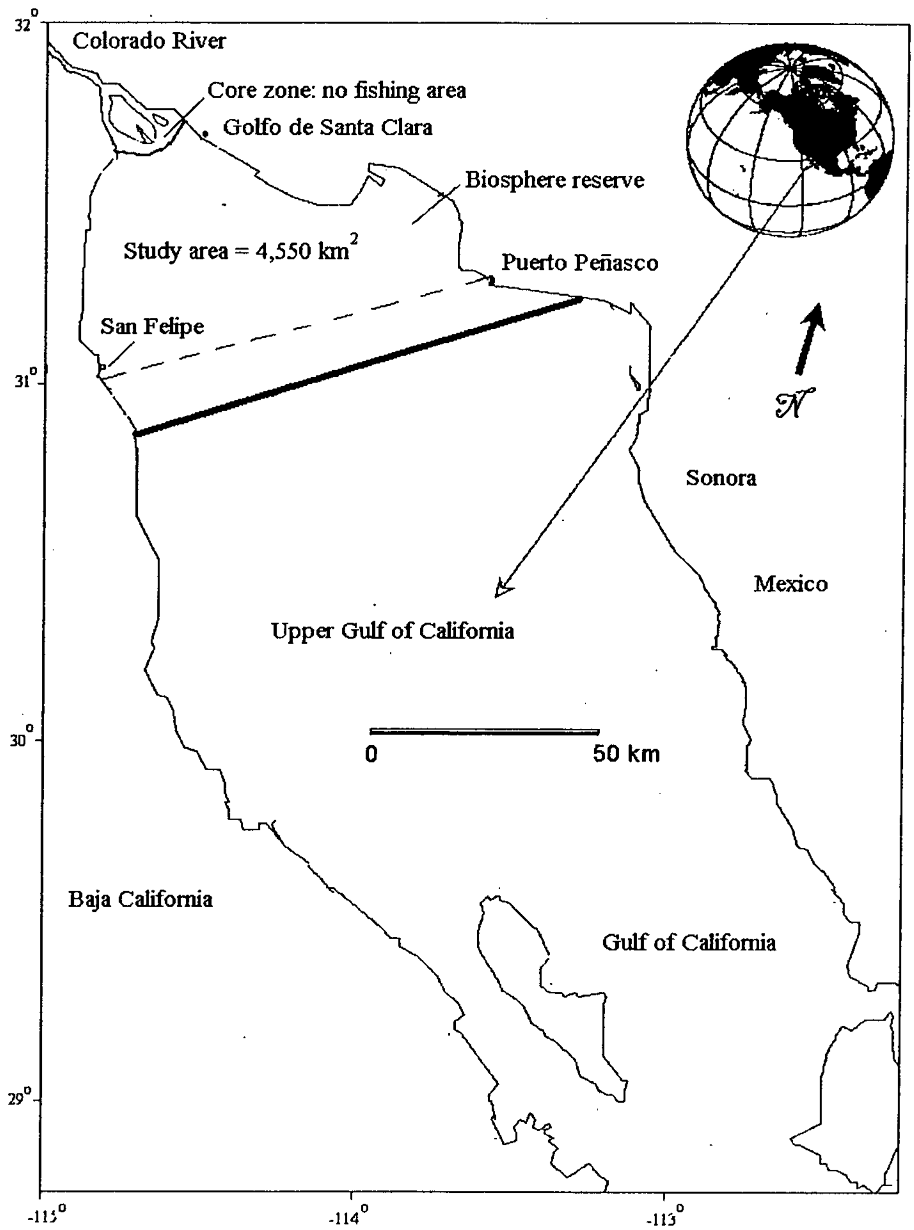

Figure 1. Gulf of California (or 'Sea of Cortez') NW Mexico. The bold line represents the a area of 4,550 km^2 produced by the historical influence of the Colorado River (70 km from the river's mouth). Significant places referred to in the text are shown. The dashed line represents the Biosphere Reserve declared in 1993 by the Mexican government to protect the delta and marine fauna of the northern gulf, including the endemic species of vaquita porpoise (*Phocoena sinus*) and giant gulf croaker (*Totoaba macdonaldi*). Core zone is a no fishing area.

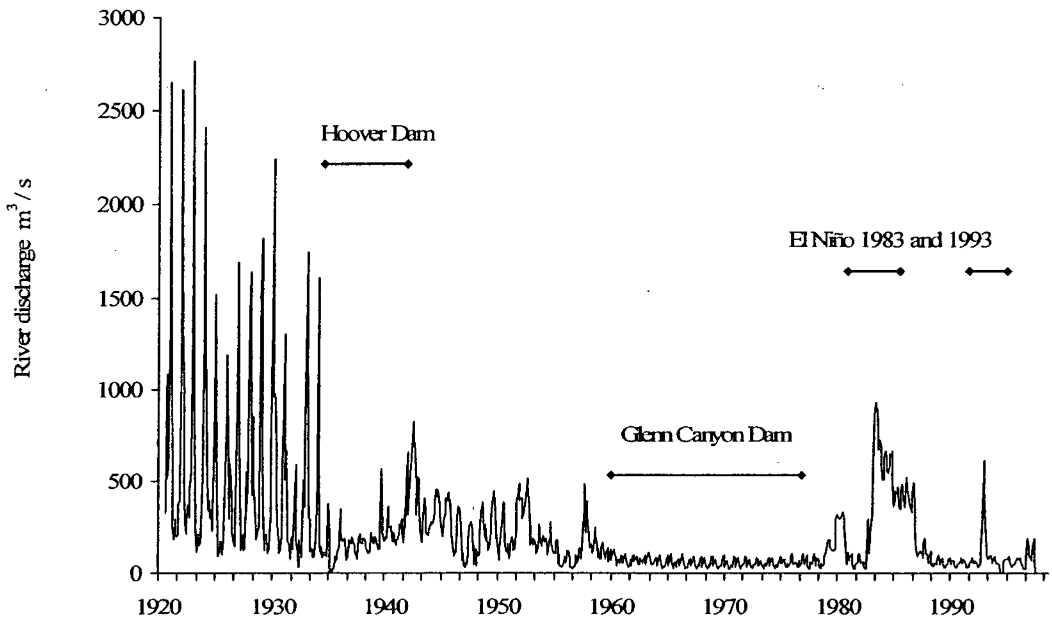

Figure 2. Annual discharge of the Colorado River below the Hoover Dam over 80 years. The horizontal bars represent the years when the Hoover Dam (1934) and Glenn Canyon Dam (1960) were completed. Note that an increase of freshwater was delivered into the upper Gulf during strong precipitation events like El Niño 1982-83 and 1993 (Data from Lavín and Badan, 1997; Lavín and Sánchez, 1999).

2. 2. *The fisheries of the upper Gulf of California.*

Despite the adverse conditions resulting from the diversion of fresh water, nutrients, and sediments from the Colorado River since the 1920s, the productivity of the upper Gulf of California has been challenged by its years of exploitation. Although today's activities such as tourism and farming are important, fishing is still the main economic activity, with more than 70 species of fish, mollusk, crustacean and echinoderm exploited. The upper Gulf provides 15% of Mexico's total landings, a significant amount considering that Mexico produces 1.3 million metric tonnes of fish per year and is among the world's 20 leading fish producers (Hernández and Kempton, 2003).

Major fisheries in these waters started at the beginning of the 20^{th} Century. The last 80 years have seem significant changes in fishing methods, efficiency and intensity. In the 1920s, canoes were used to capture totoaba with silk and cotton nets under an importation agreement with the US. These were replaced slowly in the late 1950s by large nylon gillnets, while outboard motors allowed larger vessels and longer trips that continued until the fishery collapsed in 1977. The fishery has remained closed since then, though illegal totoaba fishing is known to have taken place during at least the last decade (D'Agrosa 1995; Cisneros-Mata *et al.,* 1997).

Soon after the totoaba fishery was initiated, shrimp trawlers from the central Gulf (Guaymas, Sonora) started to fish in the upper Gulf, and the first company to buy and commercialize shrimp began in 1920 under Japanese owners. Today, the shrimp trawl fishery represents the principal source of income in the upper Gulf, followed by a highly diverse, mixed and opportunistic small-scale fleet that now exceeds 800 boats, employing gillnets, longlines, traps and hookah diving. These boats fish at all trophic levels, causing fishing mortalities from top predators to benthic filter feeders. There are three small fishing ports in the upper Gulf of California, San Felipe, Puerto Peñasco and El Golfo de Santa Clara (Fig. 1). Also, the indigenous Cocopá community has been fishing in the delta. Today, the 225 Cocopá fishers are the only people allowed by Mexican law to fish in the core zone of the Biosphere Reserve (Cudney-Bueno and Turk, 1998; Ballinas, 2002). A detailed description of the Cocopá community is presented in Chapter III.

Some small pelagic species in the central and northern Gulf have been negatively impacted by climate fluctuations (Cisneros-Mata and Hammann, 1995; López-Martínez *et al.*, 2003). A notable example was documented in the central Gulf with the Pacific sardines (*Sardinops Sagax caeruleus*) the most important species in the Gulf wet fish fishery. This fishery declined dramatically just after the 1983 El Niño, as can be seen from the national fishery statistics (Hernandez and Kempton, 2003). Chapter V discusses the role of climate and large scale changes in the productivity of the upper Gulf, including specific documented cases and simulations obtained from the models.

2.2.1. *Fisheries crises in the upper Gulf of California.*

In 80 years of exploitation, three major crises occurred in uncontrolled fisheries in the upper Gulf. The first disaster: the collapse of the totoaba fishery, occurred in the early 1970s (Fig. 3) when this species was nearly driven to extinction. A second major crisis occurred during the mid 1980s when enormous schools of Pacific sharp-nose shark vanished (Cudney-Bueno and Turk, 1998). The third fishery collapse came just a couple of years later, when a sudden decline in the production (from 560 tonnes in 1988 to 235 tonnes in 1990) of shrimp was detected (Fig 4). A catastrophic mix of low stock levels, too many fishers and no incentives to conserve the resources resulted in the collapse of the shrimp fishery, which brought about the bankruptcy of BANPESCA, a Mexican federal bank that administrated the fisheries (Hernández and Kempton, 2003). In an attempt to restore the ecology and economy of the upper Gulf of California, the Mexican government declared the upper Gulf a protected area, thus establishing the Colorado River Delta and upper Gulf of California Biosphere Reserve (Diario Oficial, 1993; McGuire and Greenberg, 1993).

During the last 50 years, fisheries catches in the southern Gulf have gradually shifted from long-lived, high trophic level species to short-lived, low trophic species (Fig. 5; Sala *et al.*, 2004); a global pattern that has been described as a worldwide tendency called 'fishing down marine food webs' (Pauly *et al.* 1998a, 1998b; 2000a; Myers and Worm, 2003). The scenario found in the upper Gulf is no different; the results obtained indicated an overall reduction of 0.2 trophic levels in the catches recorded in the last 50 years, with a clear decline of top predators (sharks and totoaba) during the 1970-80s and an increase in the catch of low trophic species such as corvinas, chano and crabs (these results are detailed in full in section 4 of this chapter). Sala *et al.* (2004) pointed out that the coastal fisheries of the southern Gulf of California are unsustainable, and their management needs to be re-evaluated to prevent further degradation of coastal food webs. These recommendations are supported by the results obtained in this document, and they could be easily extended to the UGC.

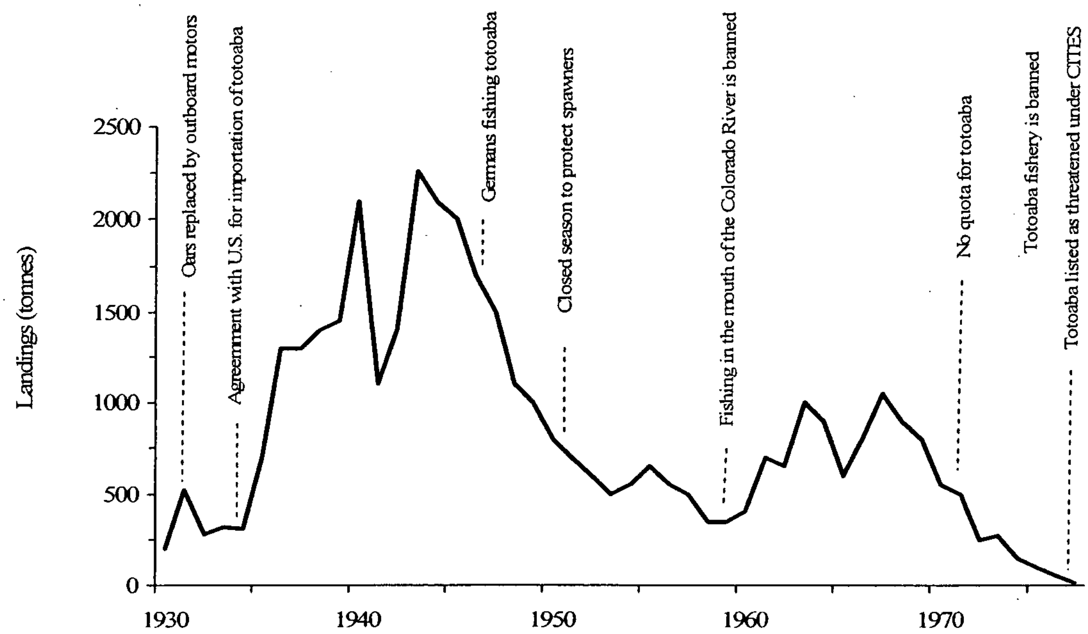

Figure 3. Historical time series of landings of the endemic giant gulf croaker or totoaba (*Totoaba macdonaldi*) in the Gulf of California. This species was exploited from the 1920s until its virtual extinction in the late 1970s. Data from Flanagan and Hendrickson (1976).

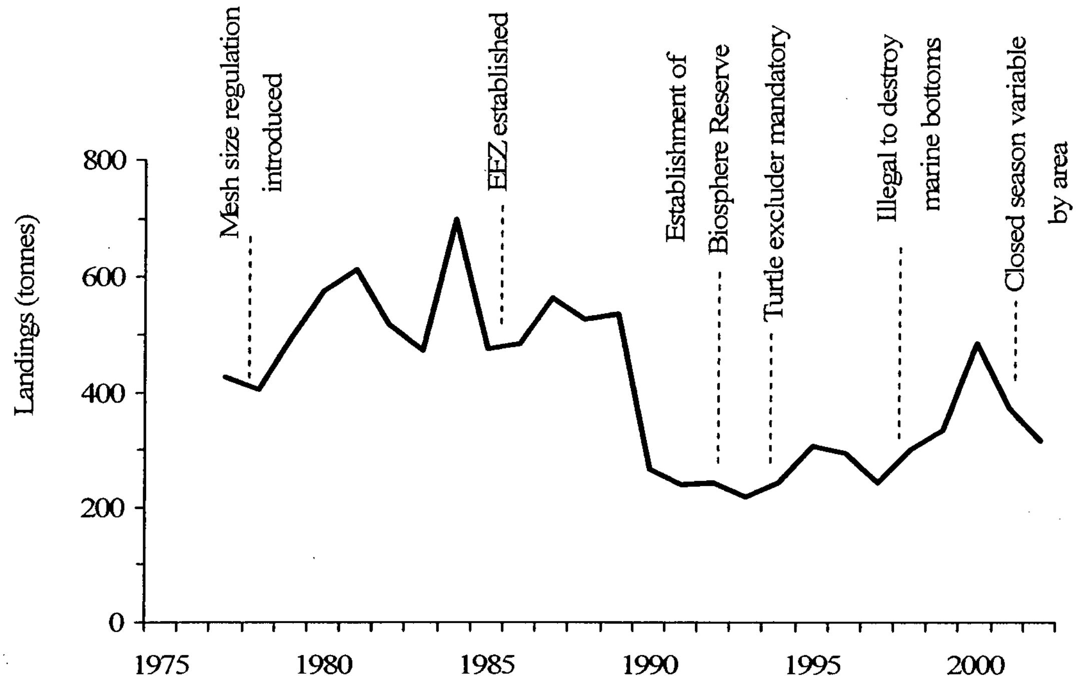

Figure 4. Annual landing of shrimps (*Peneaus stylirostris* and *P. californensis*) in one of the most important ports in the northern Gulf of California, San Felipe (Baja California). During the late 1980s a dramatic crisis in the production of shrimp resulted in the Mexican government declaring the upper Gulf of California (including the Colorado River Delta) a Biosphere Reserve in 1993. Data provided by CRIP-Ensenada.

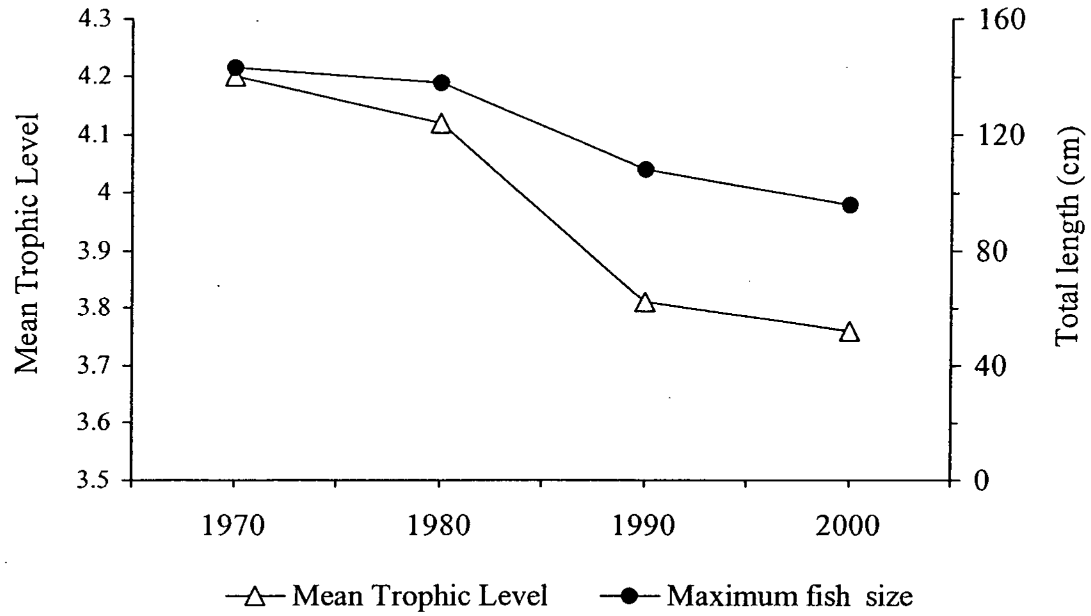

Figure 5. Temporal changes in mean trophic level and maximum fish size (total length) of coastal fisheries landings in the Southern Gulf of California. Data retrieved from Sala *et al.*, 2004.

2.2.2. First steps to address illegal and unreported catches in the Gulf of California.

Illegal and unreported fishing occurs in practically all marine ecosystems and, unfortunately, the Gulf of California is no exception. The Mexican authorities declared in 2002 that, for some resources, illegal fishing can reach up to 30 percent of the total production (Weiner, 2002). This increases the threat to already over-exploited organisms, and makes it critically important to include estimates of illegal and unreported catches in the trophic simulation models.

Since marine fisheries began in the Gulf of California, foreign fleets have been a major factor in the sharp decline of large predators such sharks and totoaba. Before and after World War II, American ships openly exploited every school of tuna and every swarm of sardines that they could find, along with sea lions taken for pet food and the extensive use

of shark's livers for vitamins and iron. Japanese fleets also fished sardines and sharks intensely in the Gulf (Steinbeck, 1940; Magallón-Barajas, 1987). Those activities clearly marked the rise of unregulated fisheries in the Gulf.

Law enforcement was lax, and economic development strategies that changed with successive governments, resulted in decades of practically unregulated fishing. In the 1990s, the Mexican government took the first steps to create effective systems of licensing and permits. Using the Mexican Navy to police the outlaws, the government created biosphere reserves along the Gulf, incorporated accurate fishing seasons, established mandatory turtle excluder devices (TEDs) in commercial shrimp trawlers, and created international committees for the recovery of endangered species. One of the most important regulations was to create the National Fisheries Chart (CNP) in 2000 in attempt to reverse the increasing fishing pressure.

This section presents qualitative estimations of misreported and unreported catches of the principal species exploited in the Gulf (totoaba, shrimps, sharks, sardines and squids), based on the history of their exploitation. While the incentives to misreport catches and estimates presented here are open to discussion, they do represent a critical first step in the analysis of extent of illegal fishing and design of effective measures to combat IUU fishing in the Gulf of California.

2.2.1.1. *Methods.*

Intensive historical research was conducted to summarize the history of fisheries in the Gulf of California from 1900 to 2004. The review included a wide range of information, from scientific and historical documents to published interviews. The compiled history includes pelagic fisheries (sardine, *Opistonema libertate*, and anchovies, *Anchoa hellery*, *A. eschiana*), bottom trawling fisheries (blue and brown shrimps) and the historical fishery of totoaba divided by decades from 1900 to 1970, and by five year periods from 1970 to 2004. Relevant aspects in social development, changes in technology and

management regimens in the Gulf were also synthesized. This information is presented in Appendix 1.

The 80 years of integrated history and important historical changes in Mexican regulatory regimens since the 1920s were employed to estimate incentives to misreport catches only from Mexican vessels in the Gulf (this analysis did not consider the American and Japanese fleets that were fishing from the 1920s to the 1960s). Table 1 presents three possible categories to misreport catches: (1) Discards; (2) Illegal; and (3) Unmandated. These categories were defined according to the criteria proposed for estimating illegal and unreported catches from marine ecosystems by Pitcher *et al.* (2002).

Incentives to misreport can occur due to a broad spectrum of motives, from changes in technology (i.e. processing facilities) or regulations (i.e. change in quotas), to changes in the market (i.e. discarding low value fish) and social factors (some species are for local consumption). Table 1 presents qualitative estimations of misreporting catches. Up arrows indicate an incentive to misreport, down arrows indicate incentive not to misreport the catches. Table 1 includes a brief description of the circumstances that could produce a possible incentive to misreport the landings.

Table 2 gives estimates of misreporting of the six principal exploited species - totoaba, shrimp, sharks, sardines, squid and demersal resources – in the Gulf of California from 1920 to 2003: these estimates are presented in a qualitative fashion, ranked in the following gross categories: None (0-1%), Low (1-3%), Low/Medium (2-6%), Medium (3-12%); Medium/High (4-24%) and High (5-25%). These estimates were utilized for each of the three categories mentioned (discard, illegal and unreported). To convert the qualitative estimates presented in Table 2 to a meaningful shape, a series of anchor points is needed at least for the last periods. Unfortunately, at the current stage of this project, no quantitative anchor estimates for the magnitude of illegal landings were obtained. Future work and collaboration with Mexican authorities will be needed to quantify total extractions. The qualitative estimates were used to get an exploratory approximation of

the misreported catches. Historical catch data series of totoaba (1930s to 1970s), shrimp (1950s to 2003) and the landings from 1974 to 2003 reported by the Institute of National Fisheries, Mexico (INP) were multiplied by the percentage of misreporting the catches presented in Table 2. The total extractions estimated for the species considered were incorporated into the three trophic ecosystem models (1950, 1980, 2000) developed in this project.

2.2.2.2. *Results*

The exploratory results obtained suggest that the catches of sharks reported in the Gulf of California may have been underestimated within a range of 1-25%; a value that includes both discards and illegal fishing. The upper limit of this range was mainly concentrated from 1975-85, and an important reduction of IUU activities was apparent at the beginning of the 1990s (Fig. 6). The landings of sharks reported by the INP for the three main ports in the upper Gulf in 2000 were approximately 0.17 t/km^2/year. This value was multiplied by the 25% of missing catch estimated and a total extraction of 0.23 t/km^2/year was applied to the Ecopath model for present day conditions in the upper Gulf. Also, Figure 6 presents the IUU catches calculated for totoaba since the 1920s until its collapse in 1977, and those values were employed in the 1950 and 1980 trophic models constructed in the region.

In the case of shrimp catches, this fishery is under tight regulation, including law enforcement by the Mexican Navy in the upper Gulf. IUU catches for this resource were estimated in the range of 1-14% of the total production for the upper Gulf. The history of its exploitation indicated that higher incentives to misreport the catches occurred during 1977-1987 and just before the shrimp collapse at the end of the 1990s. Apparently, the regulations established in the early 1990s have reduced IUU fishing of this resource at least in the northern Gulf. Figure 7 presents the total estimated extraction of shrimp in the upper Gulf (San Felipe). The official catch of shrimp (blue shrimp) reported by the INP in the upper Gulf (three ports) was approximately 0.70 t/km^2/year, and so when the IUU estimation was applied, a catch of 0.82 t/km^2/year was estimated. This value was included

in the 2000 Ecopath model (Section 3 of this chapter). Historical background, data consulted and incentives to misreport suggest that IUU catches for the sardine, squid and demersal resources (crabs, octopus, clams and sea cucumber) fisheries are low, probably less than 5-10%. Figure 8 shows the percentage of IUU fishing in the upper Gulf for the most exploited species considered in this exploratory analysis.

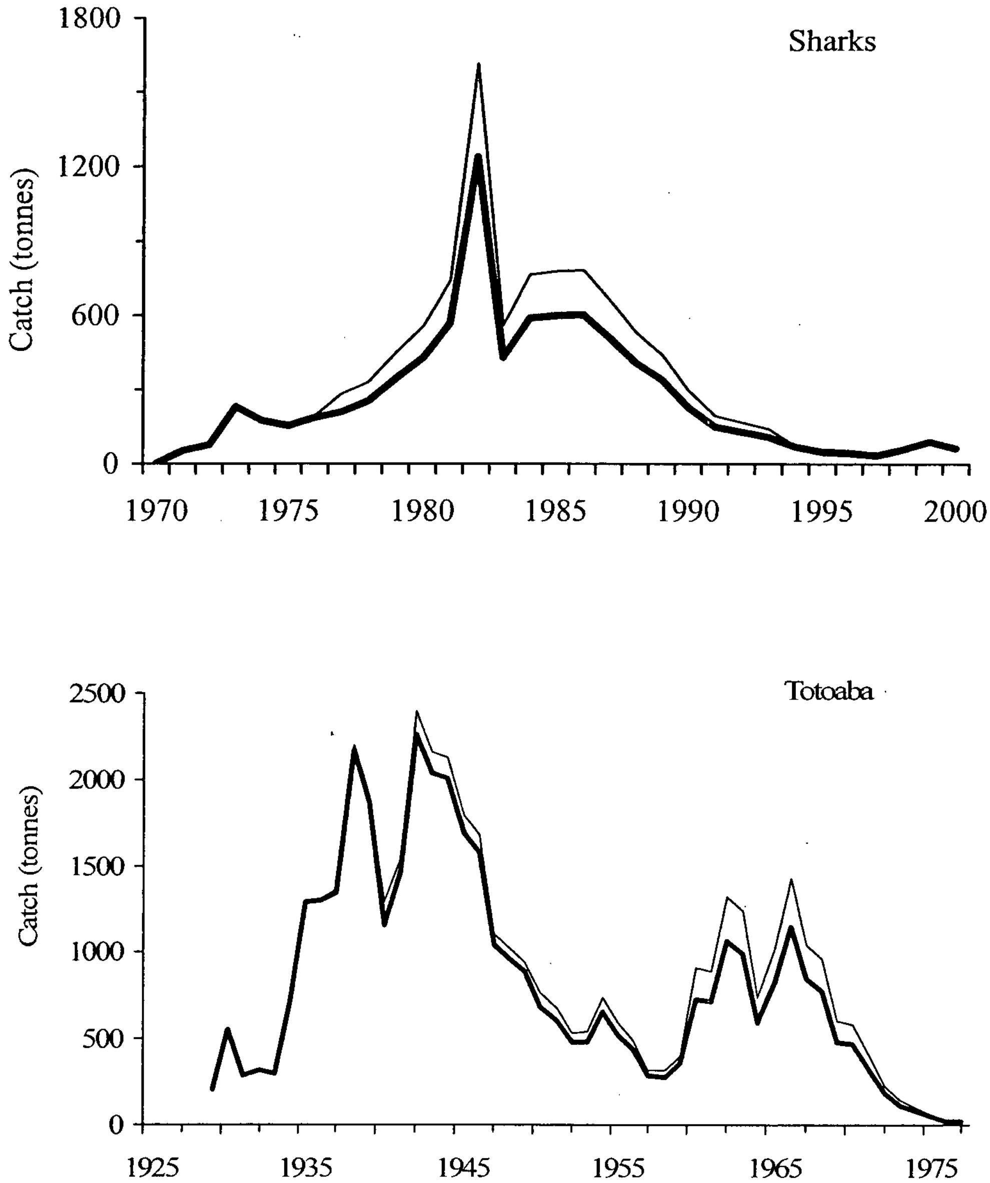

Figure 6. Estimated total extraction (landings reported + IUU fishing) of shark (upper) and totoaba (bottom) in the northern Gulf of California (thin line) in comparison to reported catch (thick line). The total estimated extractions of totoaba and sharks were utilized in the models of the upper Gulf for the 1950s and 1980s.

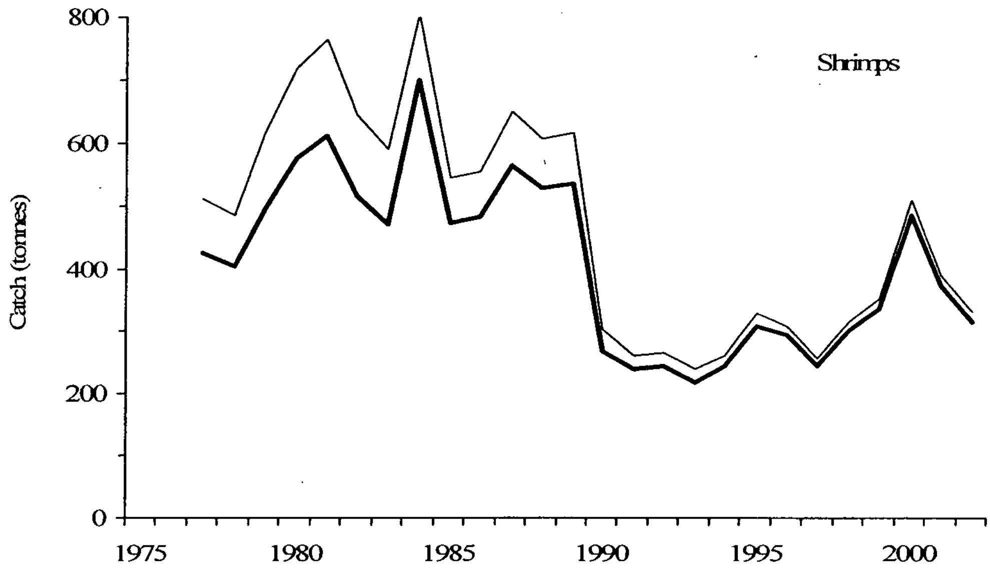

Figure 7. Estimated total extraction (landings reported + IUU fishing) of shrimp in the region of San Felipe, Northern Gulf of California (thin line) in comparison to reported catch (thick line). IUU was higher during the 1970s. Apparently, regulations established since the early 1990s have reduced IUU fishing of shrimp, at least in the Northern Gulf of California.

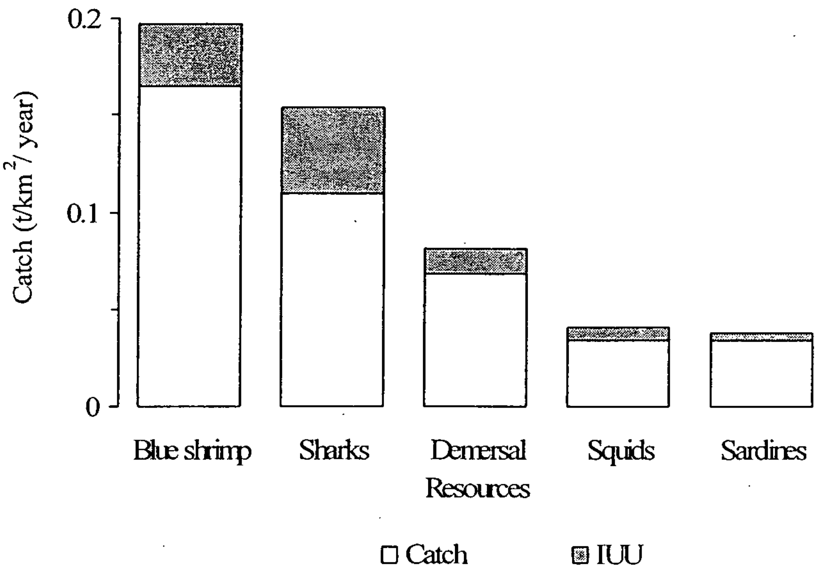

Figure 8. Proportion of IUU fishing estimated for five resources in the upper Gulf of California in 2000. The total harvest estimated for these resources (landings reported + IUU) were the input values (landings) employed in the Ecopath model for present day conditions (Chapter II, section 3).

2.2.2.3. *Discussion*

The results presented in this section must be taken as preliminary; nevertheless they exhibit some trends in the incentives to misreport catches during the history of the Gulf of California fisheries. Illegal, discards, and unreported catches in the Gulf are a current problem that Mexican authorities are attempting to tackle. For example, there were about 1,200 permits (in mid 1990s) for boats in the Gulf of California and Pacific Ocean, and it is estimated that 20 to 30 percent of their catch was being taken illegally (Weiner, 2002).

During the last decade, the Mexican government has taken initiatives to combat the ecological and economic crises that occurred during the late 1980s in the Northern Gulf. New regulations include establishing a Biosphere Reserve in the upper section of the Gulf, and creating the NOM (Mexican Official Standards) as an instrument to manage the most important fisheries and to avoid an increasing trend in fishing effort. Furthermore, it has enforced a mandatory use of turtle excluder devices, founded international committees for the recovery of the vaquita (CIRVA), created variable closed seasons for shrimp by area and deploys the Mexican Navy to patrol areas of ecological and economic interest.

From 1994 to 2000, the National Consultative Committee for Sustainable Fisheries (Mexico) promoted the use of NOMs for 14 fisheries in Mexico, including regulations such as permits, gear specifications, season and area closures, size and quota limits. It has also established sanctions including administrative sanctions or judicial penalties for illegal fishers; however, the reason that only 14 fisheries are regulated by NOMs is because of the length of time required by federal law to consult all the stakeholders, before implementing the NOM (Hernández and Kempton, 2004). These regulations marked the birth of a new administration that not only tried to include scientific participation by management but also tried to stop the tendency to change the programs and fisheries policies every six years after each presidential election. All of these structural changes implemented since 1994 had the goal of reducing fishing effort for most of the fisheries in Mexico, but in a parallel way, they have the potential to reduce

IUU (illegal, unregulated and unreported) fishing. Perhaps, some obstacles are still present: inadequate scientific resources to address many artisanal fisheries, lack of local government participation in management, and refusal by government scientists to share detailed data (Hernández and Kempton, 2004). The current fisheries policies implemented in Mexico seem to respond to long-term problems, and at least in theory, stop the growth of illegal fishing documented during the 1970s and 1980s.

Incentives and estimates for unreported catches presented here require more accurate and detailed information from the dozens of fishing camps along the Gulf, especially as to how their catches are registered by local offices and how their reports are sent to the National Fisheries Institute. Direct consultation with skippers and crew on Gulf fishing vessels will definitely play an important role in abating or eliminating IUU fishing. However, these estimations are open to discussion and collaboration from Mexican authorities. A clear need of anchor points has been expressed to convert the qualitative estimations to misreport the catches to values that can provide confidence intervals throughout a Monte Carlo simulation based on likely error ranges, as suggested by Pitcher *et al.*, 2002 and Ainsworth and Pitcher 2005. In the next stage, this IUU project must try to establish anchor points in order to quantify the impact of IUU fishing and obtain a better approximation of the total extraction in the Gulf of California. A quantitative estimation of IUU fishing activities is just one of a series of effective measures to combat this problem in the Gulf of California and worldwide. After all, the Gulf of California is recognized not only by its cultural relevance to Mexico, i.e., providing fishing for hundreds of years to several indigenous communities, but also by its richness in producing 40% of the total marine production in Mexico. Consequently, there is an obligation to estimate the true magnitude of illegal and unreported fishing.

Table 1. Summary of qualitative estimates of unreported catches. Up arrows indicate an incentive to misreport, down arrows indicate an incentive to report correctly. A brief description of the circumstances that could produce the incentive to misreport landings is included. Numbers correspond to the reference numbers presented in Appendix 1.

Year	Regulation or Management regime	Other
1920-1929	Agreement between U.S. and Mexico for importation of totoaba (↑) (52).	Totoaba sport fishery began (↑)(11). Totoaba fishery in the central Gulf started to decline, so that 6 German fishermen followed totoaba migration to the upper Gulf (↑) (11). Totoaba juveniles taken accidentally during shrimp fishing (↑)(13). High price of totoaba meat in US and Asian markets. Change to outboard motors (↑) (39).
1930-1939	Closed season for penaeid shrimp first introduced (↓) (10).	Japanese trawlers fishing in the Mexican Pacific coast and located the main trawling areas in the same decade (↑)(14). 17 sardine boats modified for shrimp fishing (↑)(14).
1940-1949	Closed season for totoaba from April to May to protect spawners (↓)(52).	"Before and After World War II, American and Japanese ships took every school of tuna and every swarm of sardines they could, along with sea lions for pet food and sharks to use the livers to remedy iron-poor or tired-blood" (↑) (8 in 9).
1950-1959	1955 a new Biosphere Reserve's nuclear zone was established, (↓) (10).	1950 shrimp fishery (offshore and small scale sectors) grew exponentially (↑)(14). Double-ring trawls introduced into the shrimp fishery (↑) (14).
1960-1969		Shrimp fishery expanded to the mouth of the GoC (↑) (14). Late 1960s Shrimp trawls fishermen gradually reduce mesh size (implies increase of bycatch) (↑) (16).
1970-1974	No regulatory measures which fix catch quotas for totoaba units(↑)(38).	Mexican immigration to the Gulf in a kind of 'Gold Rush' for shrimp which was known as 'Pink Gold Rush' (↑)(1). Refuge zone declared in 1955 now (1974) declared a reserve zone banning all fishing in the core zone (↓)(32).
1975-1979	Mexican Law protect totoaba. Fishing banned (↓) (18). Mesh size regulation introduced in 1977 as a management measure in the shrimp trawl fishery (↓)(16).	Drastic declines in totoaba, commercial and sport fishing was outlawed, but totoaba gillnetting continued until 1990s and it was a primary cause of incidental kills of vaquita (↑) (49).Unknown de number of small boats (pangas) fishing in the GoC, but there is an estimation of 5,000 - 7,000 pangas fishing (↑)(19). Institute of National fisheries, Mexico (Instituto Nacional de la Pesca, INP) began monitoring programs to evaluate shrimp spawning and recruitment each year until 1987(↓)(14).
1985-1989	EEZ (Economic Exclusive Zone) established (↓)(60).	Approximately, 24,000 sharks killed in 1987 in Central GoC (↑)(24). 161 tonnes of totoaba poached in 1985 (↑)(64).

Table 1. Continuation.

Year	Regulation or Management regime	Other
1990 - 1994	Trawler forced to use turtle- and finfish excluder devices (↓)(15). PROFEPA - government environmental enforcement agency more vigilant on activities in the Reserve (↓)(6).	Inshore fleet of the upper GoC began to hammer chano (*M. megalops*) to supply the Asian market for surimi (↑)(15, 27). Increase of sport fishing in the upper Gulf (↑) (1). Shark camps in the central Gulf grew exponentially, with > 200,000 sharks killed between 1985-93 (↑)(24). Near collapse of shrimp fishery provoked diversification of small scale fishing activity and target species switch (↑)(6, 56,). Establishment of the Biosphere Reserve, UGC(↓) (12). Use of radar to fish sardine (69).
1995 - 1999	Turtle excluder devices mandatory in commercial shrimp fishery (↓) (7, 44). No fishing in the core area of the Biosphere Reserve, also, no trawling in depths lower than 9m (↓) (26).	Shrimp trawlers and sardine purse seines fishing squids with appropriate gear (↑)(58). Estimated 200,000 tonnes of bycatch for the GoC catch (↑)(28). Mexico created CIRVA: International Committee for the recovery of the Vaquita (↓) (26). Use of GPS technology to track banks and fishing sites (69).
2000	CNP (National Fisheries Chart) established no more increments in fishing effort in the upper Gulf with 700 tonnes of shrimp per year (↓) (26).	It is difficult to know the real number of boats fishing the GoC because they can move easily from state to state bordering the Gulf, and cross it from side to side following target species (↓) (62).
2001	For the first time the closed season for shrimps was variable by area (↓) (46, 49).	More than 1,600 km of gillnet were sold in Sonora (Central Gulf) (↑)(9). As many as 150 turtles per day were harvested and killed during the peak of the season (just in San Carlos/Guaymas area-Central GoC) (↑)(9).
2002	Trawling activity banned in the Biosphere Reserve (↓) (26, 62).	"Fishermen, businessmen, scientists and even some federal officials say at least 12,000 unregulated fishing boats, probably more, now at large in the GoC "(↑)(62). Jerónimo Ramos, the National Fisheries commissioner said about 1,200 permits existed for boats in the GoC and Pacific Ocean, estimating 20-30% of the catch was being taken illegally (↑)(9).
2003		PROFEPA confiscated 11,000 kg of turtle in the upper Gulf during 8 days)(↑)(30). CONAPESCA gave 2,400 permits for shrimp fishing for the season 2002-03,but there are between 6,000 to 7,000 boats fishing shrimps in the GoC, all year around (including closed season) (↑) (30).

Table 2. Incentives for Mexican vessels in the Gulf of California to misreport their catches. These incentives were classified in the following categories: None (N 0-1%), Low (L, 1-3%), Low/Medium (L/M, 2-6%), Medium (M, 3-12%); Medium/High (M/H, 4-24%) and High (H, 5-25%). The numbers next to the incentives refer to the footnotes.

Species	Type	1920-29	1930-39	1940-49	1950-59	1960-69	1970-74	1975-79	1980-84	1985-89	1990-94	1995-99	2000-03
Totoaba	Discard	L	L	L/M	M [13, 15]	L	L	L [24]	L [24]	L	N	N	N
	Illegal	N	N/L [5]	M [4, 7, 8, 9]	L/M [11]	M/H [18]	M [20, 21]	L [23]	L [23, 32]	L [23]	N/L [23, 49]	N/L [76]	N
	Unmandated	L	L	L	L	N/L	N	N	N	N	N	N	N
Shrimp	Discard	L [1]	L [2]	L	L [14]	L	M [19]	L/M [26]	L/M [35]	L/M	L/M [43, 48]	L/M [53, 55]	L/M [62]
	Illegal	L	M [3,4,5]	M [7, 8, 9]	M [10, 15]	M [16]	M [19]	M/L [29, 30]	L/M [33,3, 72]	L/M [40]	L/M [74, 77]	L [76]/ M [52]	M/H [77,60,61,43, 75]
	Unmandated	N	N	N	N	N	N	N	N	N	N	N	N
Shark	Discard			N	N	N	N/L	N/L	L [33]	L	L/M [46, 50]	H [51]	H [58]
	Illegal			L [7, 8, 9]	L	L/M	L/M	M/H [28]	H [28]	H [38,39]	H [74,39, 50, 73]	M [76]/ H [51]	H [59,60,61, 4, 77, 78]
	Unmandated			N	N	N	N	N	N	N	N/L	N/L	N/L
Sardines	Discard			N	N	N	N	N	N	N	N	N	N
	Illegal			M [4, 8]	L	M [17]	L [22]	L [25, 26]	L [34]	N [40]	N	N [56]	N/L [66]
	Unmandated			N	N	N	N	N	N	N	N	N	N
Squid	Discard						*N*	*L* [68]	*L*	*N*	*N*	*N*	*N*
	Illegal						*L* [67]	*L/M* [68]	*L/M* [69]	*N/L*	*L/M* [73, 74]	*L* [76]/ *M* [79]	*N/L* [71, 77, 7]
	Unmandated						*N*	*N*	*N*	*N*	*N*	*N*	*N*
Demersal Resources	Discard							N	L [43]	L [43]	H [42, 44]	L/N	N/L
	Illegal							N [31]	L [37]	M/H [41]	M/H [41, 47, 72, 74]	M [76]/ H [54,77]	M/H [57, 60]
	Unmandated							L	L	L	L	L	L

Table 2. Continuation.

Footnotes:

1. In 1923 shrimp fishery starts with totoaba juveniles taken accidentally (Majallón-Barajas, 1997).
2. Bycatch of Vaquita began (Vidal, 1995).
3. 17 sardine boats modified for shrimp fishing (Majallón-Barajas, 1997).
4. Japanese trawlers fishing the Mexican Pacific coast locate the main trawling areas during this decade (Majallón-Barajas, 1997).
5. The most important changes in boats during the development of fishery in the GoC was the use of outboard motors for small boats were formerly propelled by oars at the end of the 1920s (Chute, 1928; Chute, 1930).
6. Closed season for totoaba from March to May to protect spawners (Cisneros-Mata *et al.*, 1995).
7. American ships took every school of tuna, sardine and shark that they could (Steinbeck, 1940 in Shwartz, 2003).
8. The Japanese (besides Americans) came too during 1940s (Majallón-Barajas, 1997).
9. Completion of Highway 8 in 1942 and the railroad in 1947 increased sales into U.S. markets (Boyer, 1996).
10. 1950 shrimp fishery (offshore and small scale sectors) grew exponentially. Poorly recorded (Majallón-Barajas, 1997).
11. A new Biosphere Reserve nuclear zone was established (1955) in the upper GoC, fishing in the mouth of the Colorado River is prohibited (Diario Oficial de la Federación, 1955).
12. Closed season for totoaba changed according to its abundance (Cisneros-Mata *et al.*, 1995).
13. Totoaba landings start to decline (Cisneros-Mata *et al.*, 1995).
14. Double-ring trawls introduced in the shrimp fishery (Majallón-Barajas, 1997).
15. In 1955, the shrimp CPUE (Catch/Boat) had its maximum in Guaymas (central GoC), the number of shrimp boats is unknown, but estimated around 800 (Majallón-Barajas, 1997).
16. Shrimp fishery expanded to the mouth of the GoC
17. Sardine fishmeal plants and canneries installed in Guaymas, central GoC (Cisneros-Mata *et al.*, 1995).
18. Although prohibited by law, dynamite is also used to kill totoaba directly (Ramírez, 1962).
19. High shrimp prices; there was a Mexican immigration to the GoC in a kind of 'Gold Rush' for shrimp which was known as 'Pink Gold rush' (Boyer, 1996).
20. Approximately 30 large boats (shrimp trawlers) dedicated partially or exclusively to totoaba fishing in the UGC (Arvízu and Chávez, 1970).
21. No regulatory measures to set catch quotas for totoaba or to limit the number of fishing units (Arvízu and Chávez, 1970).
22. Pacific sardine fleet moved to Guaymas (central GoC) for fishing during the winter season (Cisneros-Mata *et al.*, 1995).
23. Mexican Law protected totoaba – all fishing banned (Diario Oficial de la Federación, 1975).
24. Totoaba gillnetting continued until 1990's and it was a primary cause of incidental kills of vaquita (Cisneros-Mata *et al.*, 1995).
25. Increase of activity of the Pacific sardine fleet in the GoC (Cisneros-Mata *et al.*, 1995).
26. Mesh size regulation in the trawl fishery introduced in 1977 as a management measure in the shrimp trawl fishery (Lluch-Belda, 1977).
27. Approximately 28 Peruvian boats entered to the GoC after the collapse of the Peruvian anchovy fishery (Cisneros-Mata *et al.*, 1995).
28. Monofilament gill nets became the tool of the panga fishermen; 5,000 - 7,000 pangas fishing in the GoC (Sea Watch, 2003b).
29. The Institute of National Fisheries, Mexico (INP) began monitoring programs to evaluate shrimp spawning and recruitment each year (Majallón-Barajas, 1997).
30. 344 000 tonnes of bycatch in the shrimp fishery from 1977-80 (Grande-Vidal, 1980).
31. 1978 started the commercial exploitation of demersal resources in the GoC with 12 trawlers (Grande-Vidal, 1980).
32. Still fishing totoaba (Campoy-Fabela, 2002).
33. 35 vaquitas killed per year (1985-1992) in shark gillnets (Vidal, 1995).

34. Expansion of the Pacific sardine fishery in the GoC (Cisneros-Mata *et al.*, 1995).
35. Increase of the Pacific shrimp catches reaching levels similar to the peak ones (Morales-Bojorquez, 2001).
36. More than 80% of the total catch of shrimp in Mexico is caught in the GoC (Majallón-Barajas, 1997).
37. It has begun the commercial fishery of demersal resources with a potential biomass exploitable of order of 1,374,000 tonnes per year (Grande-Vidal, 1980).
38. Between 1987 and 1989, 10 pangas caught 8,000-10,000 sharks each season in San Francisquito, central GoC (Sea Watch, 2003c).
39. Between 1985 and 1993 over 200,000 sharks were killed in GoC (Sea Watch, 2003c).
40. Drastic decline of Pacific sardine fishery in the GoC (Cisneros-Mata *et al.*, 1995).
41. Increase of demersal fishing, where chano represents 16% of the finfish fishery in the UGC (Instituto Nacional de Pesca, 2000).
42. Tonnes of chano and other species left to rot on the sandy streets of the Golfo de Santa Clara, UGC (McGuire and Valdéz-Gardea, 1997).
43. Not enough ice and equipment to process and freeze the landings in the UGC (personal communication from fishers interviewed, 2003).
44. 12 vaquitas were killed in 1993 during 8 months of chano fishing in the UGC (McGuire and Valdéz-Gardea, 1997).
45. Trawler activities forced to use turtle- and finfish excluder devices (Diario Oficial de la Federación, 1992).
46. In 1992, the Mexican authorities banned the use of gillnets with a mesh size > 25 cm (Diario Oficial de la Federación, 1992).
47. Gulf corvina (*Cynoscion othonopterus*), return in large numbers to the upper Gulf after 40 years (Vázquez-León and McGuire, 1993).
48. Shrimp bycatch ratio estimated at 1:10 (Brusca *et al.*, 2001).
49. Establishment of the upper Gulf of California/ Colorado River delta Biosphere Reserve. In its core zone: all commercial fisheries banned. Increased regulations for most fisheries (Reserva de la Biosfera y alto Golfo de California, 2003).
50. In 1994, a gillnet fleet backed by unknown financiers appeared in Sonora, fishermen and scientists say it slaughters thousands of sharks solely for their fins ($300 a pound in Asian markets; Weiner, 2002).
51. In 1995, almost no shark at all in central GoC, the big shark processors moved to their next target (Sea Watch, 2003c, d).
52. Trawlers forced to carry turtle-excluder devices and no fishing in the core area of the Biosphere Reserve, also, no trawling in esteros or depths lower 5 fathoms (~9 m) (Campoy-Fabela, 2002).
53. Turtle excluder devices mandatory in commercial shrimp fishery (Vidal, 1995).
54. At least 70 species of fish, mollusks, crustaceans and echinoderms are regularly caught by the artisanal fleet in the UGC, approximately 40% of these are designated for international market (Cudney-Bueno, 1998).
55. Estimated 200,000 tonnes of bycatch in the shrimp fishery for the GoC (Anuario de Pesca, 1996).
56. Drastic drop in the Monterrey sardine landings (Sánchez-Velazco *et al.*, 2002).
57. It is difficult to know the real number of boats fishing in the GoC (López-Martínez *et al.*, 1999).
58. As many as 150 turtles per day being harvested and killed during the peak of the season in central GoC (Weiner, 2002).
59. More than 1,600 km of gillnet were sold in Sonora (central GoC; Weiner, 2002).
60. Jerónimo Ramos, the National Fisheries Commissioner said about 1,200 permits existed for boats in the GoC and Pacific Ocean, estimating 20-30% of the catch was being taken illegally (Weiner, 2002).
61. Fishers, businessmen, scientists and even some federal officials say at least 12,000 unregulated fishing boats in the GoC (Weiner, 2002).
62. Ratio between shrimp and discarded fauna is 1:10, using turtles and finfish excluder devises could be 1:6 (Campoy-Fabela, 2002).
63. 140 shrimp boats in the UGC, but an undetermined number of boats from other parts (Guaymas, Topolobampo, Mazatlan, Yavaros) enter to the Reserve (Campoy-Fabela, 2002).

64. PROFEPA confiscated 11,000 kg of turtle (corvina) in the UGC during 8 days (NOTIMEX, 2003).
65. CONAPESCA gave 2,400 permits for shrimp fishing for the season 2002-03, but there are between 6,000 to 7,000 boats fishing shrimps in the GoC, all year around (including closed season; Velázco-Rodríguez, 2003).
66. There is no control for foreign boats in the GoC, it is necessary to make a record of these boats (Velázco-Rodríguez, 2003).
67. Jumbo squid fishery in central GoC began, fishing from April to June (Morales-Bojorquez *et al.*, 2001).
68. Japanese vessels appeared in 1979 fishing squid (Ramírez, 1985).
69. Jumbo squid fishery collapsed, associated with over fishing, recruitment and El Niño, 1982-83. (Morales-Bojorquez *et al.*, 2001).
70. Shrimp trawlers and sardine purse seines fishing squids with appropriate gear (Markaida and Sosa-Nishizaki, 2001).
71. Squid fishery almost disappeared from the central GoC at the end of 1990s (Morales-Bojorquez *et al.*, 2001).
72. During 1980s Federal Legislation gave exclusive rights of shrimp exploitation to cooperatives (avoiding private investment); this policy produced an evident increase of shrimp catches that in most of the cases was a product for international market (Hernández and Kempton, 2003).
73. Most of the fisheries status for Mexico was uncertain (Hernández and Kempton, 2003).
74. In early 1990s, the federal agency in charge of fisheries demonstrated signals of inefficiency, two elements determined such inefficiency, the fishery policy from 1970 did not change significantly and the growth in artisanal fisheries created problems of monitoring and enforcing law (Hernández and Kempton, 2003).
75. 500 shrimp trawlers estimated to fish inside the Biosphere Reserve (Anonymous, 2002).
76. SEMARNAP created the National Consultative Committee for Sustainable Fisheries to institutionalize the participation of fishers, scientists and other stakeholders, such as local authorities and NOG's (SEMARNAP. 1998).
77. NOM's were not enough to correct the over-exploitation trend that more than 80% of the fisheries in Mexico was undergoing, where only 14 fisheries in the country were regulated under NOM's (Hernández and Kempton, 2003).
78. The NFC (National Fisheries Chart) shows that 82% of Mexican fisheries are fully or over-exploited, justifying policies to reduce the effort in all those fisheries (Hernández and Kempton, 2003).

2.3. An ecosystem model of trophic structure and fisheries interactions in the upper Gulf of California and Colorado River Delta for 1995-2000.

2.3.1. Introduction

The declines and losses of major fish stocks worldwide attributable to intensive industrial fishing in the past century have been extensively documented. This point to a dismal failure of management based on traditional single species stock assessment has been unsuccessful, pointing out the failure of fishery science during the past decades with dozens of collapses and crises. Unfortunately, the fisheries in Mexico are no different. 82% of the stocks are reportedly overexploited with an increasing growth in the small-scale fishing effort (Hernández and Kempton, 2005).

The single species approach, applied in the Gulf of California and in Mexico in general, is inappropriate for tropical small-scale fisheries as it was developed for temperate regions where single species fisheries are prevalent and where fish are harvested by a few gear types at most (Munro, 1979). A different scenario is presented in tropical regions where typically the fisheries have a multi-species, multi-gear nature and harvesting occurs at different stages of the life histories. The single species approach is also weak as it fails to consider the following critical aspects: (1) biological and environmental interactions occurring at varying temporal and spatial scales; (2) the changes produced by humans (e.g. habitat degradation, pollution and increasing fishing); and (3), the influence of short- or long-term climatic changes, resulting in limited fishery policies with narrow views and unrealistic expectations of levels of sustainable exploitation. Disappointingly, fishery science has failed to avoid fish stock collapses, generating frustration among scientists during the last decade and the desire to use new approaches with the potential to answer more complex, ecosystem-based questions and ultimately to manage and rebuild ecosystems (Pitcher 1998a, 1998b, Pitcher and Pauly, 1998).

For these reasons, this study uses ecosystem modelling to explore the structure, function and energetic dynamics of the upper Gulf of California. The modelling is focused on trophic interactions among 50 functional groups of the upper Gulf, providing assessments of energy fluxes and partitioning of resources among predator groups, including extractions by fisheries. In addition, a network analysis quantifies flows for a comparison with models of past ecosystems in the upper Gulf, examining changes in form and function that are important for management. The mass-balance ecosystem model for the Gulf of California in 1995-2000 developed in this chapter covers more than 120 species and is used as the basis for a dynamic model that can track and emulate changes caused by water diversion, fishing and fluctuations in climate over the past 60 years.

In an ecosystem context, the health and integrity (associated with both structure and function) of the upper Gulf of California and Colorado River Delta are discussed through a present-day food web model that describes the interplay of predators, prey and fisheries. Chapter III presents models of the system as it was in 1950 and 1980 and presents the 'Back to the Future' approach to restoration ecology.

2.3.2. Methods.

The first step to building a mass-balance trophic model with Ecopath is to define the objective and the area. Here, the objective was to create an ecosystem model to evaluate the impacts of the water diversion from the Colorado River. The area was defined according to the historical Colorado River influence in the upper Gulf that used to flow 70 km from the river's mouth (Carbajal *et al.*, 1997; Lavín, 1999; Flessa, 2001). This pattern produces a triangular area of nearly 4,550 km^2 (Fig. 1). Approximately 80% of the model area was declared a Biosphere Reserve in 1993 (Diario Oficial, 1993). All commercial fisheries are prohibited in the core zone of this reserve except for traditional practices by the aboriginal *Cocopá* people living in the Delta, and clam harvesting by local residents, (SEMARNAT, 2003). The model area includes the three coastal fishing communities of San Felipe, El Golfo de Santa Clara and Puerto Peñasco (Fig. 1), which

have supported important fisheries since 1920 and which now provide 15% of the national fish production.

2.3.2.1. Constructing the trophic model for the CRD/UGC ecosystem.

Ecopath mass-balance models account for trophic interactions averaged over a pre-defined area and time period at multiple trophic levels among organisms within the ecosystem area defined (Polovina, 1984; Christensen and Pauly, 1992; Christensen *et al.*, 2000). Dynamic routines (named Ecosim and Ecospace) use the mass-balanced model generated by Ecopath to simulate changes that may include effects of human activities, including fisheries, other disturbances and stressors on the biological components in the system (Walters *et al.*, 1997; 2000), providing an effective tool for evaluating ecosystem impacts. More comprehensive descriptions of the basis, scope and pitfalls of Ecopath with Ecosim (EwE) can be found in Christensen and Walters (2004) and the freely distributed software is available at *www.ecopath.org*. According to the methodology proposed by Christensen and Walters (2004), the general approach of EwE is summarized below:

Ecopath uses a series of simultaneous linear equations, one for each functional group to quantify the energetic flows among trophic groups according to the law of conservation of mass or energy (Equation 1). The net production of a functional group equals the total mass removed by its predators and fisheries plus its net migration and its energy or mass that flows to detritus. The master equation is described as:

Production – Predation - Other mortality - Exports = 0

or

Production=Fishing mortality + Predation mortality + Other mortality + Biomass Accumulation + Net Migration

$$B_i \cdot PB_i \cdot EE_i = Y_i + \Sigma B_j \cdot (Q/B)_j \cdot DC_{ij} + EX_i$$

Where:

B_i and B_j are biomasses of prey (i) and predators (j) respectively;

PB_i is the production/biomass ratio, equivalent to total mortality (Z) in most circumstances (Allen, 1971);

EE_i is the ecotrophic efficiency or the proportion of production utilized in the system

Y_i is the fisheries catch per unit area and time.

Q/B_j is the consumption/biomass ratio of the predator

DC_{ij} is the fraction of prey i in the diet of predator j

EX_i is the export of i.

The input data for any particular functional group are: P/B, Q/B, B, EE and DC; however, Ecopath requires DC as an input while any one of the other parameters can be estimated by mass balance if the other three are known. Normally EE is estimated, but in cases when biomass is unknown, it is possible to obtain an estimate by making an assumption about EE (0.95, for example). However, in the case of particular groups in this UGC model (totoaba, vaquita porpoise and blue shrimp), ontogenetic changes were represented by splitting these groups into recruits or pre-adults and adults.

2.3.2.2. Aggregation of functional groups.

The 120 species considered in the model were organized into groups based on the functional roles of the species, and which took their food habits and natural history into consideration. Groups with important conservation values were kept as individual groups, producing single groups for vaquita porpoises (*Phocoena sinus*), giant gulf croakers or totoaba (*T. macdonaldi*) and the endemic clam of the Colorado delta, *Mulina coloradensis*. In the case of species of economic interest, such as a gulf croaker called 'chano' (*Micropogonias megalops*), and the blue (*P. stylirostris*), brown (*P. californiensis*) and rock (*Sycyonia spp*) species of shrimp were also modeled as unique groups. In order to evaluate the importance of the estuarine waters of the upper Gulf as a nursery area (Cisneros-Mata *et al.*, 1995; Glenn; Calderón-Aguilera *et al.*, 2000; Aragón-

Noriega *et al.*, 2001, Brusca *et al.*, Glenn *et al.*, 2001) juveniles or pre-adults of vaquita porpoise, totoaba and shrimps were also included in the model. Our classification resulted in 50 ecological groups (Table 6).

2.3.2.3. Sources of the basic input parameters.

Biomass: Biomass (B), the ratio of production to biomass (P/B), and the ratio of consumption to biomass (Q/B) represent the 'basic input parameters' of Ecopath models. Numerous sources of information were used to estimate these basic parameters. In general, biomasses were estimated mainly from the databases generated from 1991 to 1995 by the INP (National fisheries Institute, Mexico). This institution, through its regional center of fishery research located in Ensenada, Baja California (CRIP-Ensenada), has conducted several surveys and trawl samplings in the shallow waters of the upper Gulf to estimate biomasses of benthic organisms: INP generated maps of abundance per unit area for more than 20 species from 1991-1995 (CRIP-Ensenada, 1995).

The following sections summarize how the biomass was estimated for the principal model groups (phytoplankton, zooplankton, benthos, seabirds, fish marine mammals and detritus). A detailed list of the references employed for constructing the 50 functional groups in our Gulf of California model is presented in Appendix 9.

Primary production: The biomass of primary producers was the sum of the four producers considered in the model (phytoplankton, macro-algae, seagrasses and seaweeds). Primary production in the UGC can be two or three times greater than that in the open Pacific or Atlantic Oceans at similar latitudes (Zeitzchel, 1969). Biomass estimates were based on local surveys by Millán-Núñez, *et a*l. (1999), where, according to chlorophyll concentrations and depths registered during their surveys, average primary production associated with phytoplankton was estimated as 28.9 t/km^2. The intertidal macrophyte communities of the upper Gulf comprise more than

19 major taxa (mainly *Ulva, Porphyra, Sargassum, and Colpomenia*) covering more than 60% of the rocky habitats (Littler and Littler, 1981). The mean macrophyte net production per square metre reported in 1980 for the upper Gulf was 47.9 mg C day^{-1} (equivalent to a standing biomass of 1.145 t/km^2), a value that was employed for the 1980 and 2000 models (see Chapter III for details). No production estimates for macrophytes, seagrasses and seaweeds were found for the time period modeled (1995-2000), and so their biomasses were estimated by Ecopath (Table 5). Nevertheless, these groups are well distributed throughout the Gulf of California (Steward and Norris, 1981; Little and Little, 1981; Meling-Lopez and Ibarra-Obando, 1999) and more research on their biomass and distribution in the upper Gulf is needed. For this reason, the biomass estimated for the early 1980s was used for this group. During the tuning and fitting of the past and present models (Chapter III), a compatible estimation of the biomass predicted for the 1980s by Ecopath is compared with that obtained from surveys and the abundance results for the 2000 model.

Zooplankton: abundances of zooplankton and microzooplankton were taken from local surveys by Farfán and Álvarez-Borrego (1992) and García-Pámanes and Lara-Lara (2001), respectively. In general, the upper Gulf is a very rich region with zooplankton biomass that can reach up to 154 mg/m^3 (Montague Island, Figure 1). An average biomass for the upper Gulf from was estimated at 26.3 t/km^2 (Farfán and Álvarez-Borrego, 1992). This functional group includes copepods *(Calanus pacificus*), cladocerans (*Penila spp*) and chaetognaths (*Saggita enflata*). P/B and Q/B ratios were taken from Chávez *et al.*, (1993) and García-Pámanes (2001), respectively.

Benthos: Information available in the literature is scarce for the benthos community in the UGC. Some biomasses of invertebrates were estimated from a rigorous study done by the INP from 1992-1995 (CRIP-Ensenada, 1995), that aimed at estimating the bycatch in shrimp trawls; estimates are provided for Cnidaria, Mollusca, Arthropoda and Echinodermata. In the absence of data between 1995-2000, information reported by Felix-Pico (1975), Romero (1980) and from Salazar-Vallejo (1990) was used

(Table 1). The *Q/B* ratios were generally estimated by using the empirical formula reported for these groups by Pauly *et al.*, 1993. Since there was no information on mortality rates for most of these groups, P/B ratios were taken from other Ecopath models for the central and northern Gulf of California (Arreguín *et al.*, 2002; Morales-Zárate, 2004).

Seabirds: abundances of seabirds on the coast and islands of the UGC were based on visual census (Peresbarbosa and Mellink, 1994; Mellink *et al.*, 1996 and 1997). During the winter of 1991, more than 100,000 birds of 36 species (most of them shorebirds, *Calidris mauri*, black skimmer, *Rhynchops* niger and American avocets, *Recurvirostra americana*) were observed in the upper Gulf (Morrison *et al.,* 1992). Due to its importance for shorebirds, the Colorado River Delta has been incorporated into the Western Hemisphere Shorebird Reserve Network. In the summer, this habitat is less important, but resident populations of brown pelican (*Pelecanus occidentalis*), double-crested cormorants (*Phalacrocorax auritus*), gulls (*Larus delawarensis*), white terns (*Sterna caspia*) are abundant (Peresbarbosa and Mellink, 1994).

For the model, seabirds were split into two gross groups. The first group is represented by shorebirds (planktivorous birds, such as *Calidris mauri,* willets, avocets, etc*)* living in the deltas located in the mouth of the rivers (less than 2% of the area modeled. The numerical abundances of this group can easily reach more than 80,000 birds during the winter (Morrison *et al.*, 1992). A conservative abundance of 40,000 resident birds with a mean body weight of 50g was used to estimate the biomass of 0.001 t/km^2 used in the Ecopath model. The second group comprises seabirds such as pelicans, gulls, cormorants. A gross estimation of 18,000 birds in the region was used (based on number of pairs of birds recorded in Montague Island by Peresbarbosa and Mellink, 1994) and using a mean body weight of 600g (mainly gulls, terns and pelicans), it results in a biomass estimated at 0.003 t/km^2.

Fish. Fish stock biomasses were estimated from different sources. In the case of demersal species, surveys done by *INP-CRIP-Ensenada* (1992-1995) were used.

Using the method of Cushing (1971) based on swept area, the maps of abundances (individual/hour) were transformed to an average biomass (t/km^2). In most cases, the 1995 survey was used as an average year and to set the biomass values for the Ecopath model. These local surveys reported the abundance of more than 20 species (juveniles and adults of totoaba, *T. macdonaldi*, corvinas *Cynoscion* spp, snappers, *Lutjanus* spp., shrimps, *Peneaus* spp., crabs, *Callinectes*, rays, *Urobatis* spp, guitarfish, *Rhinobatos* sharks, *Carcharhinus limbarus, Heterodontus* spp) with ecological and economic value and other fish with minor economic value (aggregated in the model as 'other fish'). Table 3 presents a comparison between the biomasses estimated by the INP surveys and the biomasses employed to construct the trophic models reported by Morales-Zárate *et al.* (2004) and this thesis. Figure 9 shows three examples of the species sampled (shrimp, crabs and chano) during the 1995 surveys. In some cases, and for single species (e.g. totoaba), Virtual Population Analysis (VPA) was applied to the historical time-series of catch-at-age data to estimate fishing mortalities and biomass back to 1950 (more details are presented in Chapter III).

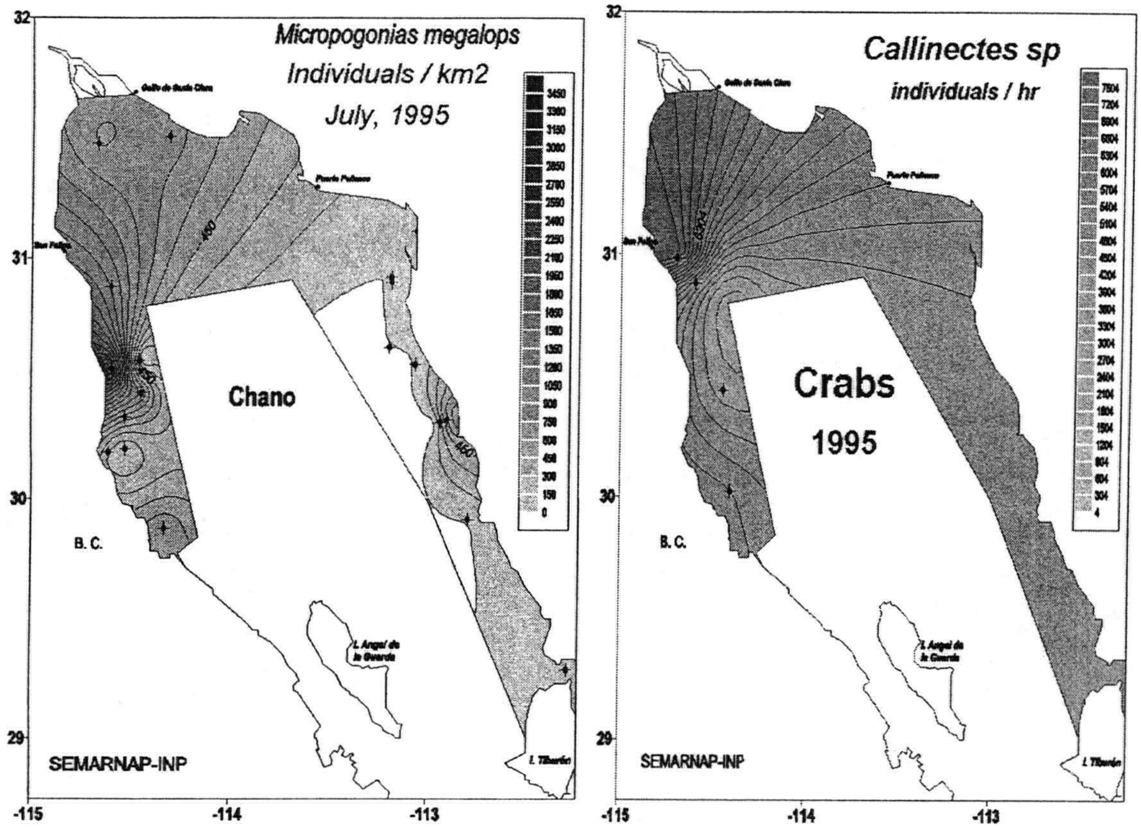

Figure 9. Contour map of abundances of chano (left) and crabs (right) in 1995. The abundance of more than 20 benthic species (crustaceans and fishes) was estimated from four years of surveys performed by the INP (Institute of National Fisheries) from 1991-1995 (CRIP-Ensenada, 1995), and these biomasses were employed in the 2000 model (maps were provided by the Institute of National Fisheries, Mexico). Maxima Abundance Scales: chano, 3600 individuals/hr; crabs, 7500 individual/hr.

Table 3. Biomasses estimated (t/km^2) from the maps of abundance generated in the Northern Gulf of California by the National Fisheries Institute and CRIP-Ensenada. Biomasses used in another Ecopath model for this region (Morales-Zárate *et al.*, 2004) are compared with those utilized in this thesis. See references for complete citations.

	Surveys 1991	1992	1994	1995	Survey average	Morales-Zárate model.	This thesis
Sharks	0.02	0.28	0.0	0.05	0.09	0.47	0.28
Serranids	0.06	0.02	0.16	0.11	0.09	0.29	0.16
Sciaenids	0.77	0.11	3.99	0.33	1.29	0.35	3.99
Rhinobatids	0.45	0.35	0.0	0.22	0.26	0.33	0.35
Rays	1.31	0.89	14.6	0.56	4.35	0.56	4.35
Flatfishes	0.02	0.02	0.33	0.05	0.10	1.51	0.33

Marine mammals. The high abundance of marine mammals is one of the reasons why the upper Gulf is recognized nationally and internationally as a 'hot spot' of diversity (Jaramillo-Legorreta *et al.*, 1999). Sea lions, *Zalophus californiensis*, are abundant from a colony off San Felipe (Baja California), and at least seven species of cetaceans were recorded after a period (1986-1987) of freshwater release from the Hoover and Gleen Canyon dams (Silber *et al.*, 1994). Biomass estimates used the numerical abundances reported by Zavála-González and Mellink, 2000 (for sea lions) and by Silber *et al.* 1994 (for dolphins and cetaceans) multiplied by the average weight for each species (Table 4). An estimate of 567 vaquitas (Jaramillo-Legorrreta, 1999) was used to estimate biomass. Tagging studies by Urban (2002) suggest that there is a permanent population of fin whale (*Balaenoptera physalus*) in the central Gulf of California that makes feeding journeys into the upper Gulf. Table 4 shows the estimated numerical abundances of marine mammals in the region.

Table 4. Numerical abundance of cetaceans in the upper Gulf of California, according to; (1) Silber *et al.* 1994; (2) Jaramillo-Legorreta *et al.*, 1999 and by (3) Zavala and Mellink, 2000. See references for complete citations.

Species	Name	Numerical abundance
Zalophus californiensis	California sea lion	20,000 [3] (Central GoC).
Delphinus delphis	Common dolphin	14,239[1]
Tursiops truncates	Bottlenose dolphin	1,416[1]
Phocoena sinus	Vaquita	567[2]
Balaenoptera physalus	Fin whale	215[1]
Balaenoptera physalus	Fin whale	215[1]
Orcinus orca	Killer whale	17[1]
Balaenoptera edeni	Bryde's whale	7[1]
Escgrictius robustus	Gray whale	3[1]

Detritus: there was no available information for detritus accumulation in the area, but an empirical relationship established by Pauly *et al.*, 1993 was used to obtain a rough estimate of this parameter:

$$\log D = 0.954 \log PP + 0.863 \log E - 2.41$$

Where D is detrital biomass in g C m^2, PP is primary production in g C m^2 year^{-1} and E is the euphotic layer depth (m). For the model, a PP = 115 gCm^2 (according to Millán *et al.*, 1999) and average E = 20 m were used. At this point, no information of irradiance has been found for the area, so the euphotic depth was estimated at 20 m. The fit of the regression equation to the data is not very good, but as suggested by Pauly *et al.*, (1993), it might be considered sufficient in cases where no other information is available. An estimation of 28.7 t/km^2 was used employed for the 2000 model, a value that seems to be reasonable, considering the more than 450 millions of metric tonnes of sediment/year that once reached the upper Gulf (Van Andel, 1964; Carbajal *et al.*, 1997; Carraquiry and Sánchez, 1999).

Production per unit of biomass (P/B)

In this kind of mass-balance model, the ratio of production to biomass, P/B is assumed to equal total mortality, Z (Allen, 1971). Therefore, this production parameter was calculated for commercial exploited stocks as the total of fishing (F) and natural mortalities (M). The P/B value for non-exploited species was obtained directly from natural mortality, as estimated from the empirical equation proposed by Pauly (1980):

$$M = K^{0.65} * L_{inf}^{-0.279} * T^{0.463}$$

where K is the von Bertalanffy growth constant; L_{inf} is the asymptotic length expressed in centimetres and T is the average water temperature in °C. The average temperature in the upper Gulf used was 23.5°C, according to the mean SST distribution for the period 1984-2000 (Lavín *et al.*, 2003). Appendix 9 presents the sources of information employed for estimations of P/B for the non-fish groups included in the model.

Consumption per unit of biomass (Q/B).

The Q/B ratio represents the food intake by a group over a specified time period (consumption) divided by its biomass. Q/B was calculated using the holistic method proposed by Pauly *et al.* (1990) was employed according to the following equation:

$$Q/B = 10.67 * 0.0313^{TK} * W_{inf}^{-0.168} * 1.38^{Pf} * 1.89^{Hd}$$

where T*K* is an expression for mean annual habitat temperature (TK=1000/T°C + 273.1); P*f* is 1.0 for top predators and zooplankton feeders; and a value of zero for other feeders. W_{inf} is the maximum weight of the fish, estimated from the asymptotic length given by FishBase (Frose and Pauly, 2000; 2001). H*d* is the food type (0 for carnivores and 1 for herbivores and detritivores).

Diet composition.

The diet composition matrix was assembled as percentage weight or volume of the annual fraction that each prey contributes to the overall diet of the predator (Christensen *et al.*, 2004). Several local reports were used, but when upper Gulf data were not specifically available, values were taken from the same species from the central or northern Gulf of California models documented previously (see appendix 9 for a complete list of references). The diet composition matrix is presented in Appendix 2.

2.3.2.4. Sources of Catch Data.

Most of the commercial fisheries catch data used in the model were provided by the regional fisheries offices of the Institute of National Fisheries located in San Felipe (Baja California), Puerto Peñasco and the Gulf of Santa Clara (Sonora). Databases for shrimps and historical landings of totoaba were obtained from the CRIP-Ensenada (Regional Fisheries Centre, Ensenada, Baja California). For some particular invertebrates (clams, *Chione* spp, *Tivela styultorum*, snails, *Strombus* spp, sea cucumber, *Brandtothuria impatiens*, octopus, *Octopus digueti*, crabs, squids, *Lolliguncula* spp) exploited by hookah divers from Puerto Peñasco, the information utilized was provided by Richard Cudney-Bueno and Peggy Turk from CEDO (Study Center of Deserts and Oasis, Sonora, Mexico) and from Cudney-Bueno and Turk-Boyer (1998). Fishing fleets were divided into eight sectors: offshore shrimp trawlers, offshore finfish fishery, artisanal shrimp (gillnet 5 cm), artisanal gillnet from 6-10 cm, artisanal gillnet higher than 10 cm artisanal long-liners, traps and hookah divers. As outlined above, illegal and unreported catches were estimated for the region according to the methodology proposed by Pitcher *et al.* (2000 & 2005). The total extractions estimated were included in the 2000 model. Recreational catches of San Felipe (and more recently in Puerto Peñasco) are probably significant in this ecosystem. A guesstimate of 5% of the official landings recorded in San Felipe was added for sharks, jacks (*Caranx* spp, *Seriola* spp), wrasses (*Halichoeres* spp), snappers, serranids (*Paralabrax* spp, *Ephinephelus* spp), corvinas, chanos and flounders (Paralichthys spp) in addition to the previous IUU adjusted estimates.

2.3.2.5. *Balancing the model.*

Model imbalance is usually signified by thermodynamically unrealistic values of output parameters. Usually, the first iteration produced values of ecotrophic efficiency (EE) greater than 1.0 (the ecotrophic efficiency represents the proportion of production that is consumed by predators, and cannot exceed 1.0). During the first run, twenty-two out of the 50 groups were thermodynamically unbalanced with an average EE of 4.66 ± 5.02 SD (range from 1.12 to 19.08). Most of the unbalanced groups were fish (13 groups) with an average EE= 2.52 ± 1.12. Invertebrates represented the most unbalanced groups (7 groups) with an average EE= 9.67± 6.64; the other two groups out of balance were sea lions and seabirds. The first step taken to achieve balance was to minimize cannibalism within groups (i.e., toothed cetaceans, including orcas and dolphins; sharks, snappers and others) liberating this energy to other groups (as suggested by Christensen *et al.* 2000). The second step was to reduce the consumption rates for those groups without local information reported; hence, the diets of their predators were adjusted in order to decrease the consumption values (shifting the consumption pressure to other preys). Since only six groups out of the 50 were unbalanced and EE ranged from 2.16 ± 1.17 SE, Q/B values were reduced between 5-15 % for the following groups: shrimps, crabs, small pelagics, corvinas, totoaba and sharks. After these changes, the model was found to be in mass-balance. Final parameters employed in the 2000 model are presented in Table 6.

2.3.2.6. *Uncertainty and model validation.*

After tuning the model, I proceeded to evaluate its consistency through the respiration to biomass ratio (R/B), which, as expected, increased with trophic levels, as actively swimming organisms have a higher R/B ratio (note that R/B does not account for specific differences in metabolic rates between marine mammals and fish groups). After I verified that the model was both balanced and consistent, the Ecoranger routine, built into the EwE software by Christensen and Walters (2004), was applied to evaluate the uncertainty

associated with all input parameters.

Using a Bayesian approach and performing several iterations using randomly selected values and specified frequency distribution (normal distribution for this model), it was possible to minimize residuals (according to the least squares criterion). The best model fitted was selected for use with the dynamic simulations in Ecosim.

The 'pedigree' routine in EwE, serves as a sensitivity analysis for documenting the effect of inputs on estimated parameters. The pedigree index (P) measures the amount of local data used (i.e., minor uncertainty in the inputs) among the five basic categories of models: Biomass (B), Production to biomass (P/B), the ratio of consumption to biomass (Q/B), and diets and catches for each of the functional groups. The range of P is from 0 for data not rooted locally to 1.0 for data that are fully rooted in local data (Christensen *et al.*, 2004). For the model presented in this paper, 227 categories from the 50 functional groups were analyzed and a value of 0.64 for this index was obtained.

2.3.3. Results.

The hundreds of trophic connections among the 50 model groups make it difficult and somewhat incomprehensible to represent them through a food web diagram; instead, Table 6 shows the basic parameters of the upper Gulf of California ecosystem. This synthesis represents the first step in evaluating the structure of the system, a potential attribute in resource management.

The ecosystem model spans more than four trophic levels. The top predators were represented by sharks larger than 120 cm (*Carcharhinus limbatus, Sphyrnia lewini, Heterodontus mexicanus*) at a trophic level of 4.2 Most of the eco-groups occur at a trophic level between 2.5 and 3.5. Of these, croakers, corvinas, rays, guitarfish, flounders, snails, murex, octopus, crabs, and shrimps are mainly dependent on detritus food chains. Given the relatively large number of groups occurring at these similar trophic levels, competitive interactions among these groups no doubt occur in addition to the predator-

prey relationships.

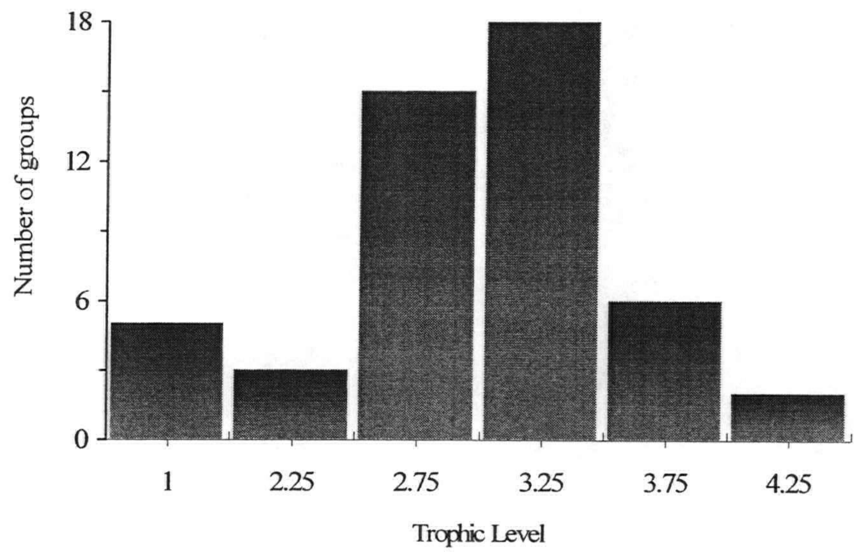

Figure 10. Trophic aggregation of the 50 groups (> 120 species) in the upper Gulf model, show that the system is largely controlled by the lower trophic levels.

2.3.3.1. Mortality: Fishing *versus* Predation.

In terms of overall predation, the mortality imposed by fishing is the second top predator. Sharks took more biomass of vertebrates than fishing from the system (0.204 t/km^2). Figure 10 illustrates the distribution of fishing mortality across the principal groups and compares this to the predation imposed by mortality for each group. Fishing pressure is spread out in all trophic levels, imposing high mortalities to top predators, but also at the bottom of the food web. The fishery is the only predator of large sharks in the upper Gulf and it removed more biomass of sharks, corvinas and chanos than natural predators. These results indicated that the fishery has a large impact on several species of the upper Gulf, including key commercial species such as shrimp, Sciaenids, scombrids, and sharks. Clearly, fishing, sharks and sea lions are major predators in the upper Gulf of California system.

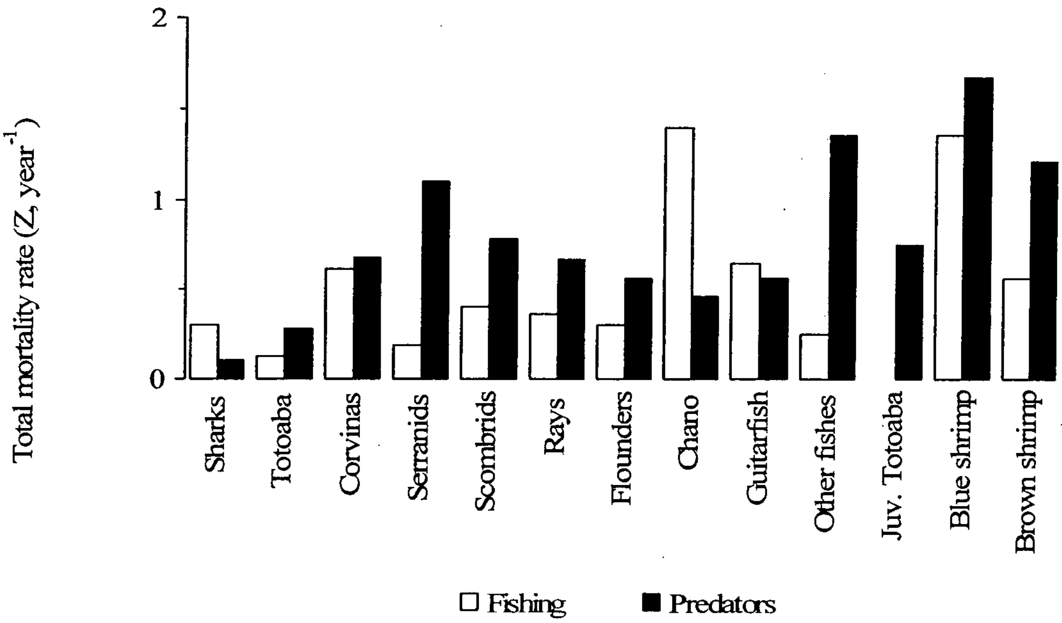

Figure 11. Comparison of fishing mortality and predation mortality rates on individual prey groups.

2.3.3.2. Network flow analysis.

Interactions among ecosystem components were evaluated using the 'mixed trophic impact' routine built into EwE (Christensen *et al.*, 2000) that displays positive or negative changes in biomass for a group when other biomasses change. In general, the groups that cause large increases are detritus, phytoplankton, seagrasses, zooplankton and chano. A summary of the mixed trophic impact results is given in Figure 12. It is important to note the impact of detritus on commercial species such as shrimps, snails, clams, crabs, octopus, chano, corvinas and more. The top predators in the system (excluding fisheries), such as sharks, totoaba, sea lions and vaquitas, had negative impacts on intermediate groups (jacks, croakers, corvinas hakes, etc), thus releasing lower groups from predation pressure. An increase in fishing by artisanal long-liners had a negative impact on large and medium sharks, but a positive effect on their prey, which can be explained by the reduction in predation and competition as noted above.

To evaluate the role of fisheries in this ecosystem, a first approach was to use this trophic impact routine. Results indicated that the fishery has a big impact on the CRD/UGC ecosystem. The large scale sector, represented by the offshore shrimp trawlers, had a negative effect on many groups, not only affecting benthic resources, but also producing a negative cascade of impacts at intermediate and high trophic levels (Fig. 13). The large range of species caught by this non-selective fishery is an important factor in determining the health and management of this area. Figure 13 dramatically shows that the diverse small-scale fishery sector (using gillnets from 2 to 8 inches, long-lines, traps and hookah divers) imposed pressure on a wide range of species (from sharks to crabs or snails). There is, however, a fundamental difference, in that the artisanal gear not only targets specific species or groups, but also has a very low discard rate, compared with approximately 7 kg (range from 2-10 kg) of discarded organisms (mainly fish) per 1 kg of shrimp by offshore trawlers. Discards represented 26% of the total catch in the system, 89% of which originated from shrimp trawling. Moreover, the highly diverse small-scale sector, at least in this region, has the ability to fish at all trophic levels, niches and eco-groups. This imposes greater fishing mortalities on most of the groups, something that needs to be considered in evaluating the total impact of the fisheries and management plans on the region.

Summary statistics for the system are presented in Table 5, and a full description of these results (flows, consumptions and indices) will be found in Chapter III as part of a comparison with models representing 1950 and 1980.

Table 5. Basic summary statistics from the network flow analysis of the 2000 model.

Parameter	Value	Units
Sum of all consumptions	2,139.2	t /km^2 /year
Sum of all exports	1,058.7	t /km^2 /year
Sum of all respiratory flows	784.1	t /km^2 /year
Sum of flows into detritus	1,197.7	t /km^2 /year
Total system throughput	5,178.3	t /km^2 /year
Net primary production	1,169	t /km^2 /year
Total biomass (excluding detritus)	1,06.5	t /km^2 /year
Total catches	12.9	t /km^2 /year
Mean trophic level of the catch	2.89	-
Gross efficiency (catch/net primary production)	0.011	-

2.3.4. Discussion.

One of the benefits of ecosystem modelling approach is the potential to identify which areas or groups in the system need more research and understanding. In the case of the CRD/UGC ecosystem, the outcomes from the unbalanced model suggest that benthic communities (polychaetes, sea cucumbers, snails, scallops, oysters, clams, murex, sea stars, octopus, crabs and others) are the weakest link. The model revealed that the benthic groups require more information about their biology, production and consumption in order to understand their ecosystem role, including their response to human activities. The trophic imbalances of these eco-groups must be resolved by a better understanding of their roles in the food web.

The mixed trophic impact analysis indicated that the fishery, as one of the three top predators in the system, had a big influence on the CRD-UGC ecosystem. The large-scale industrial fleet (mainly shrimp trawlers) not only has an impact at the lower trophic levels of benthic resources but also produces a cascade of effects that reach higher in the food

web, mainly through the high rate of discards which eliminates organisms that could otherwise be consumed by higher trophic levels. The diverse small-scale sector, on the other hand, fishes at practically all trophic levels, but the artisanal gear is more selective than offshore trawlers and there are almost no discards.

The shrimp trawler effort has been reduced in the area, and trawlers have been banned in the core zone of the biosphere reserve since the mid 1990s. However, these regulations do not seem to be sufficient, as because the small-scale sector also has impacts. All sectors of the fishery must be assessed and managed, and it is not completely accurate to label shrimp trawlers as a 'bad fishery' and the small-scale sector a 'good fishery'.

The trophic impact analysis also shows the important role of detritus in the upper Gulf for all consumer organisms and for the fishery. This response could be explained by the Colorado River delivering hundreds of millions of tonnes of nutrients and organic matter every year (180 x 10^6 t/year; van Andel, 1964). This is a key factors for promoting productivity of lower trophic levels (particularly to those groups which are linked to the detritus flows), and thus leading to higher catches.

The negative impact of predation by large fish (sharks, totoaba, scombrids, and serranids) suggests 'top-down' control (Carpenter *et al.*, 1985) in the system, but at the same time, the positive impact of benthic groups (including detritus) shows a potential for 'bottom-up' control (Carpenter *et al.*, 1985), indicating a more realistic 'mixed' control of the food web in the upper Gulf of California.

Comparison of energy flows with other marine ecosystems around Mexico supports the suggestion by Morales-Zárate *et al.* (2004) that the Northern section of the Gulf of California is a dynamic system in a mature stage of development. The total system throughput (sum of all flows) suggests that the upper Gulf is a relatively small, but highly productive system. This is corroborated by observations made over decades that the upper Gulf and delta are a feeding ground and area of protection for larval and juvenile stages of

many fish and vertebrates (Sykes, 1937; Alvarez-Borrego, 1975; Pérez-Mellado, 1980; Pedrín-Osuna *et al.*, 2001; Campoy-Fabela, 2002).

2.3.4.1. Sensitivity analysis.

The basic model parameters (B, P/B, Q/B and EE) presented in Table 6 were varied between –50% and +50% to evaluate model sensitivities. The model was insensitive (producing a response of less than 15% in the estimated parameters of other groups) to parameter changes in several groups, such as small pelagics, myctophids, wrasses, turtles, seabirds and sea cucumbers. In contrast, the model was most sensitive to groups at the top and bottom of the food web. For example, a 50% decrease in the biomass of the sharks resulted in an increase of 32% in vaquita and 42% in sea lions. Corvinas, croakers, and crabs showed similar sensitivity to a decreased biomass of totoaba. The greatest sensitivities are associated with zooplankton and accumulation of detritus. A 50% reduction in the P/B ratio of zooplankton produced an increase of 95% in the EE of phytoplankton. Unfortunately, this analysis shows that the model was most sensitive to the groups with high uncertainty concerning their biology in the upper Gulf. These groups included sharks, marine mammals, benthic communities of sessile and semi-sessile epibenthos, meiobenthos, and detritus. Also, lower trophic levels were very sensitive to changes in the simulated accumulation of detritus.

2.3.4.2. Uncertainties in the data.

Weaknesses in the biomass and diet estimations have been pointed out in previous sections of this thesis. In addition, we are unsure of the predator and prey relationships of juvenile totoaba and vaquita, perhaps the most important species of conservation concern in the UGC. Again, the model provides estimates of the role of various predators in the system (sharks, sea lions, dolphins, vaquita, serranids, scombrids and totoaba), but the diet information for some of these predators is unsatisfactory. Also, cannibalism is estimated to be less than 5% in groups such as sharks, serranids, scombrids, or Sciaenids

(including totoaba), but this needs to be calculated more carefully in the future with better biological data. The UGC has been recognized as an important nursery and reproductive habitat for several species (from totoaba to shrimps) and the predation pressure imposed on their eggs, larvae and juveniles has not been fully included in this work (only three groups of juveniles were considered in the model).

2.3.4.3. Concluding remarks.

My model of the upper Gulf of California and Colorado River Delta in 1995-2000 represents a synthesis of our current knowledge of the biota and fisheries. The results confirm that the upper Gulf is a key habitat for diversity and richness in the Gulf of California and in Mexico. Sensitivity analysis indicated that the model was sensitive to the biomass of top predators and detritus; however, if the biomasses of top predators are increased by more than 15%, the model does not balance. Hence, obtaining local biomass values from field surveys is a critical aspect for the future. Trophic impact analysis suggests that accurate estimations of productivity at lower trophic levels are equally relevant. The model also highlights many of the uncertainties concerning the biological knowledge of the area. These issues not only include all trophic levels and many of the heavily exploited species but also suggest that they have to be resolved by a better understanding of the biology. In general, the study demonstrates the benefits of exploring the role of top predators and the energy flows required to sustain their interactions in the system. It is not possible to understand the ecosystem effects of the Colorado water diversion or fishing until the interactions among the species in the food web are evaluated and understood.

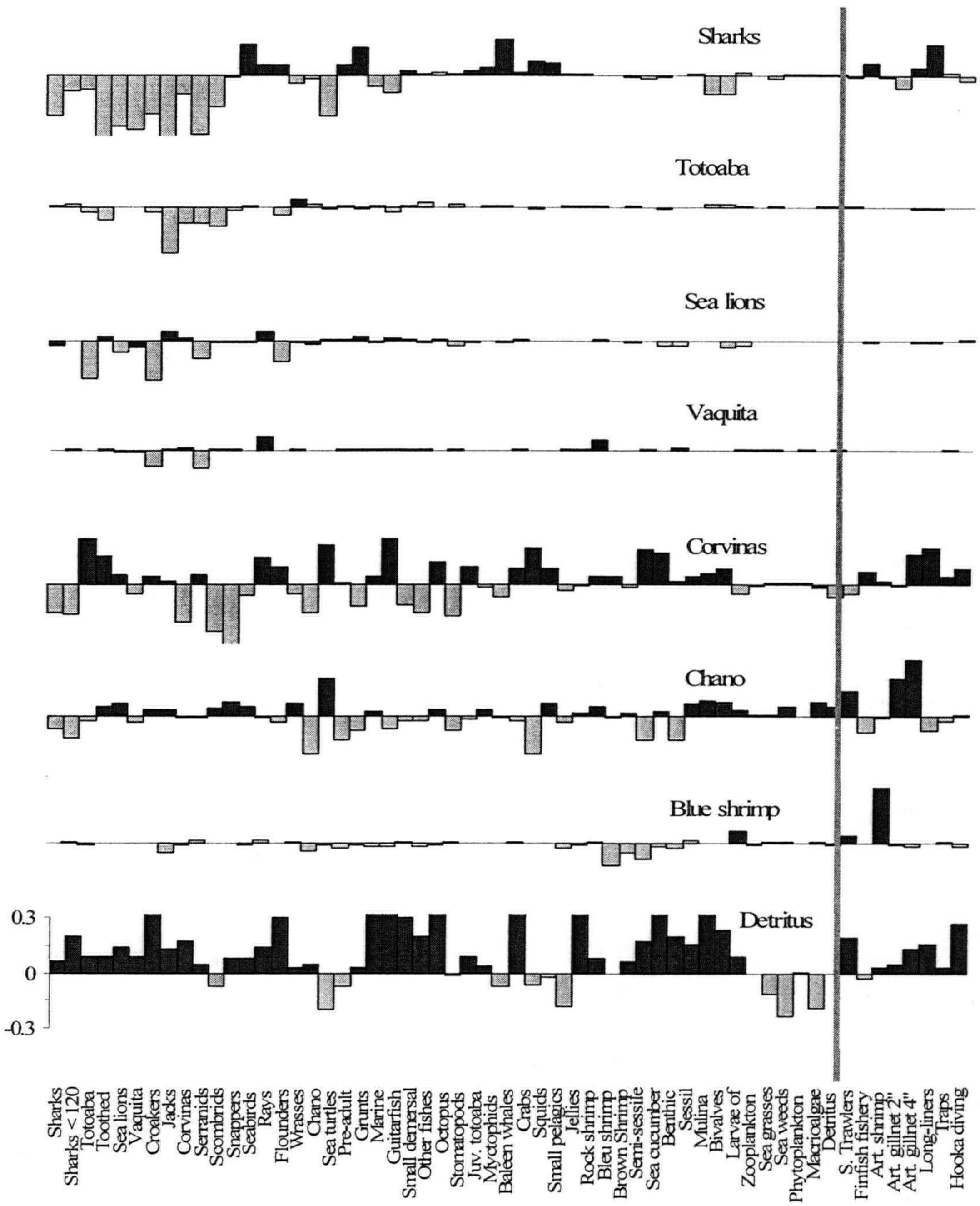

Figure 12. Mixed trophic impacts of the principal groups of the upper Gulf model, representing the direct and indirect impacts that a small increase in the biomass of the groups on the vertical axis would have on those on those on the horizontal axis. The black bars above the lines represent positive impacts, whereas the shaded bars are negative impacts. The impacts are relative, but are comparable between groups. See text for details. Fisheries are shown to right of vertical line.

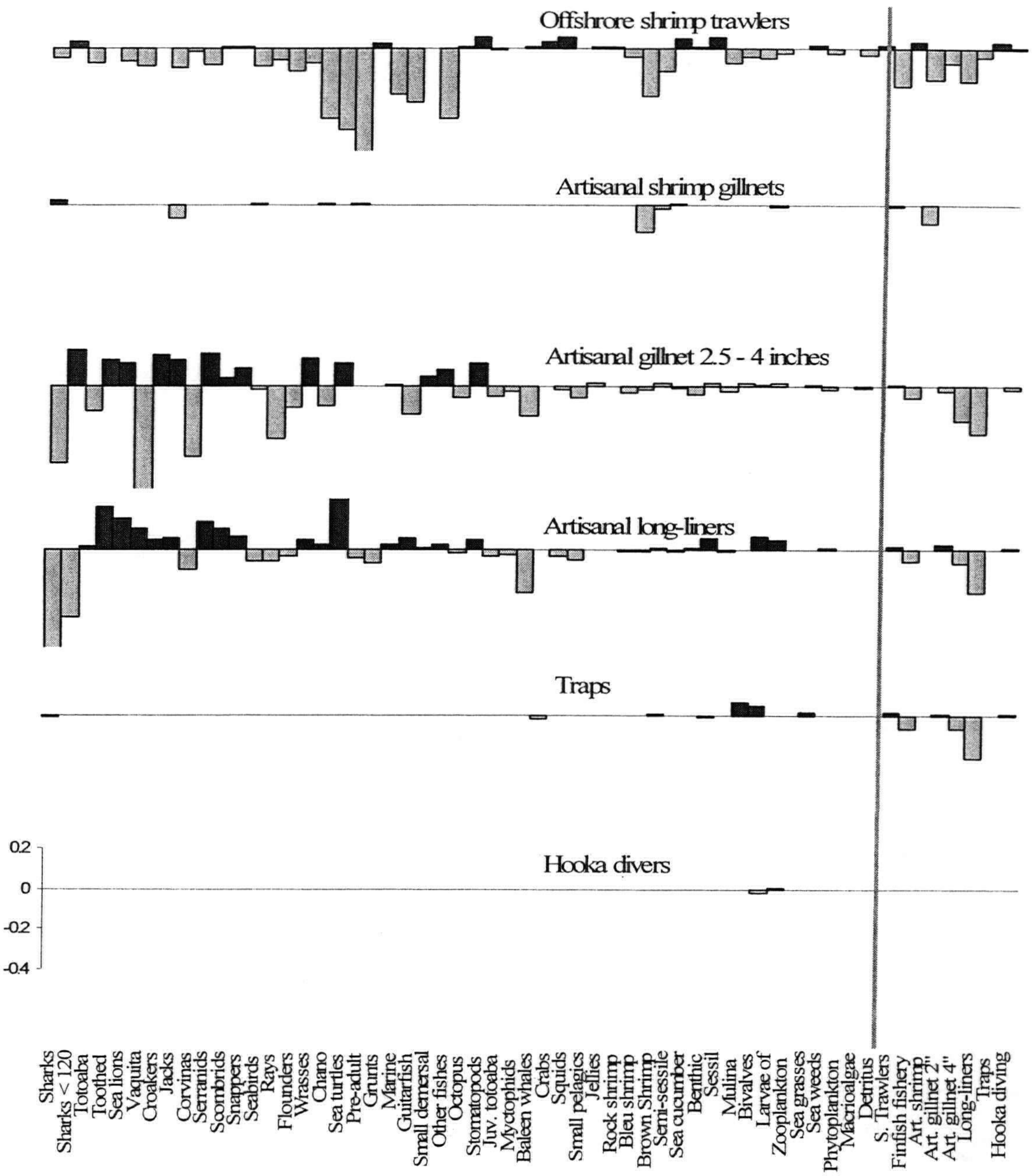

Figure 13. Mixed trophic Impacts of the eight fishing fleets included in the CRD-UGC model, representing the direct and indirect impacts that a small increase in the fleets along the vertical axis would have on the species groups on the horizontal axis. The black bars above the lines represent positive impacts, whereas the shaded bars are negative impacts. Fisheries are shown to right of vertical line.

Table 6. Basic parameters for the upper Gulf of California model. Bold numbers were parameters calculated by EwE.

Group name	Trophic level	B (t/km^2)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	EE
Seagrasses	**1.0**	**0.745**	15	-	0.68
Seaweeds	**1.0**	**1.281**	15.34	-	0.71
Phytoplankton	**1.0**	28.972	60	-	**0.85**
Macroalgae	**1.0**	1.145	60	-	**0.39**
Detritus	**1.0**	28.751	-	-	**0.21**
Benthic meoifauna	**2.0**	**6.796**	6.7	25.00	0.95
Sea cucumber	**2.0**	0.069	4.1	5.47	**0.46**
Mulina coloradensis	**2.0**	0.005	1.14	23.00	**0.31**
Bivalves	**2.0**	**0.0558**	1.14	25.00	0.95
Zooplankton	**2.1**	26.327	18	60.00	**0.59**
Juv. Blue shrimp	**2.1**	**0.137**	12	60.00	0.95
Crabs	**2.2**	1.162	3.76	10.74	**0.93**
Small demersal fish	**2.2**	**2.640**	1.821	6.81	0.95
Gerreidae	**2.2**	0.747	2.13	6.97	**0.96**
Croakers	**2.2**	1.621	0.719	3.90	**0.98**
Sessile Epibenthos	**2.3**	2.354	2.7	15.00	**0.94**
Blue shrimp	**2.3**	0.583	4	28.94	**0.92**
Brown shrimp	**2.5**	0.326	4	28.94	**0.42**
Planktivorous birds	**2.4**	0.00002	9	45.00	**0.00**
Octopus	**2.4**	0.080	3.45	9.51	**0.72**
Rock shrimp	**2.5**	0.773	4	28.94	**0.87**
Other fishes	**2.5**	6.999	1.85	6.40	**0.99**
Corvinas	**2.5**	3.988	0.76	7.80	**0.99**
Semi-sessile epibenthos	**2.6**	**1.360**	2.2	8.20	0.95
Myctophids	**2.7**	1.891	2.276	5.78	**0.76**
Guitarfish	**2.7**	0.351	1.78	6.30	**0.87**
Small pelagics	**2.7**	0.001	3.76	11.20	**0.99**
Baleen whales	**2.8**	0.021	0.05	10.90	**0.32**
Flounders	**2.8**	0.331	0.881	1.74	**0.94**
Rays	**2.8**	4.345	2.192	7.20	**0.65**
Sea turtles	**3.0**	**0.003**	0.2	3.50	0.95
Stomatopods	**3.1**	0.882	4.38	15.60	**0.90**
Jellies	**3.1**	0.376	25	40.00	**0.80**
Chano	**3.2**	1.620	1.937	9.62	**0.98**
Squids	**3.2**	0.170	4.879	22.50	**0.92**
Grunts	**3.3**	0.815	1.873	6.78	**0.88**
Serranids	**3.4**	1.253	0.164	3.23	**0.86**
Snappers	**3.4**	0.196	0.76	5.40	**0.56**
Wrasses	**3.4**	0.434	1.1	7.80	**0.51**
Juv. Totoaba	**3.5**	0.002	**2.8**	14.00	0.95
Jacks	**3.5**	0.388	0.619	3.18	**0.73**
Pre-adult Vaquita	**3.6**	0.00001	**6.0**	40.00	0.95
Seabirds	**3.6**	0.001	5.4	40.00	**0.93**
Sharks < 120 cm	**3.6**	2.990	0.35	3.20	**0.99**

Table 6. Continuation.

Group name	Trophic level	B	P/B	Q/B	EE
Vaquita	**3.6**	0.006	0.6	27.00	**0.01**
Toothed cetaceans	**3.7**	0.236	0.2	27.00	**0.79**
Sea lions	**3.8**	0.291	0.4	26.75	**0.70**
Scombrids	**3.9**	1.704	1.107	3.20	**0.98**
Totoaba	**4.0**	0.016	0.466	4.80	**0.90**
Sharks	**4.2**	0.159	0.278	3.00	**1.00**

2.4. Tuning and simulating the upper Gulf of California and Colorado River Delta ecosystem using Ecosim.

It is possible to use the mass-balance solutions from the Ecopath model to produce dynamic simulations (Ecosim) that explore the direct and indirect ecological effects of fisheries, perturbations and even scenarios of climate effects (Walters *et al.*, 1997; Christensen *et al.*, 2000; Pauly *et al.*, 2000; Walters *et al.*, 2000; Christensen and Walters, 2004), providing potential information for management and policy (Pitcher *et al.*, 2005). In Ecosim, the predator-prey interactions are mainly moderated by the vulnerability parameters (v) that reflect the relative time that prey are vulnerable to predation, representing the relative strength of bottom-up forcing (donor control, or density-dependent ratio, v = 1) and top-down control (predator control, or Lotka-Volterra, v=8); the v's can also represent an intermediate state (Walters *et al.*, 2000; Christensen and Walters, 2004). For this reason, the time of foraging is one of the parameters to consider in the tuning of the simulation models. Ecosim uses a system of differential equations that expresses flux rates among biomass pools as a function of time varying biomass and fishing rates (for equations see Walters *et al.*, 1997, 2000; Christensen *et al.*, 2004). These equations are solved using an Adams-Bashford integration routine (by default) or by Runge-Kutta 4^{th} order routine (if selected; Christensen *et al.*, 2004a). A statistical measure of goodness of fit to the time series data is measured as the sum of squared deviations (SS): this goodness of fit is generated each time Ecosim is run.

2.4.1. Tuning the 2000 UGC model.

Biomasses predicted by the Ecosim simulations can be fitted using time series data of relative abundance (e.g., catch per unit effort CPUE) or absolute abundance estimates (e.g., survey biomasses). This process known as 'tuning' provides adjusted models (based on stock assessment data) that can track changes in biomass that are known to have occurred in the past. The time series fitting uses either fishing effort or fishing mortality data as a driving factor for the Ecosim model runs.

In the case of the UGC/CRD model, it was necessary to estimate the fishing mortality from 1983 to 2000 for each exploited group in the upper Gulf (read as a CSV file). These estimations were obtained as a result of dividing the catches published (adding the illegal, unreported and unregulated fishing or IUU as a percentage estimated in Chapter II, section 2) by the National of Institute of Fisheries over the biomasses reported in the region from 1978 to 2003 (Pérez-Mellado, 1980; Magallón-Barajas, 1988; Nava-Romo, 1994; CRIP-Ensenada, 1996; López *et al.*, 1997; Aragón-Noriega *et al.*, 1999). In particular cases, such as totoaba, biomass was estimated by applying a VPA to the catch at length reported by Román-Rodríguez and Hammann (1997) and its posterior conversion to age through the von Bertalanffy growth function documented by Cisneros-Mata *et al.* (1995). This stock assessment allows the estimation of the biomass of totoaba from 1950 to 2000, used in the present day model as well as in the 1950 and 1980 models for the upper Gulf presented in Chapter III.

Fishing mortalities drive the changes in simulated catches and biomasses in the model. Biomasses estimated by surveys and stock assessments were compared to those calculated by Ecopath during the fitting routine. As the tuning process requires a continuous time-series of fishing mortality (in this case for 1978-2003), it was necessary to keep fishing mortality constant at the 1978 value (or to the earliest previous value) for those groups with no fishing mortality rate (no biomass estimation).

2.4.2. Vulnerabilities.

The second component to consider in the tuning process is the vulnerability (V) in predators/prey interactions. In general, the higher the vulnerability, the more that biomass is affected by predation (or fishing). In contrast, if prey is unable to find refuge from their predators, v will be lower. In Ecosim, the vulnerabilities are set to 1.0 for bottom-up control, while v=2.0 is considered as mixed control, and values higher than 2.0 represent top-down control (Christensen *et al.*, 2004). Based on the trophic level of each group, the vulnerabilities in the model were set initially from 1.2 to 4, and adjustments to specific groups were made after they were compared with the time-series of biomass during the tuning process.

The tuning process in the upper Gulf was also weighted by the biomasses and catches of locally-exploited species. The major weight (50%) was put on the catches of shrimps, followed by their biomass (weighted 25% higher than the rest of the groups). Shrimps receive a high emphasis because their biology and population ecology have been the subject of intense study in the upper Gulf for decades (Felix-Pico, 1975; Pérez-Mellado, 1982; Pérez-Mellado and Findley, 1985; Magallón-Barajas, 1988, CRIP-Ensenada/INP, 1996; Aragón-Noriega *et al.*, 1999; Aragón-Noriega, 2000; Aragón-Noriega and Calderón-Aguilera, 2000, 2001; Calderón-Aguilera *et al.*, 2002; Aragón and García-Juárez, 2002; SAGARPA 2003). The shrimp fishery is also the most important source of income for the upper Gulf, representing probably the best-known species in the upper Gulf and probably in the entire Sea of Cortez which accounts for 50% of Mexico's shrimp production (García-Caudillo *et al.*, 2000). Figure 14 shows the fitting for the 2000 model, where the predicted biomass of shrimps is compared with the time series of biomass observed (from surveys) in the upper Gulf [Note that fitting plots for other species are presented in Chapter IV- tuning of the 2000, 1980 and 1950 models].

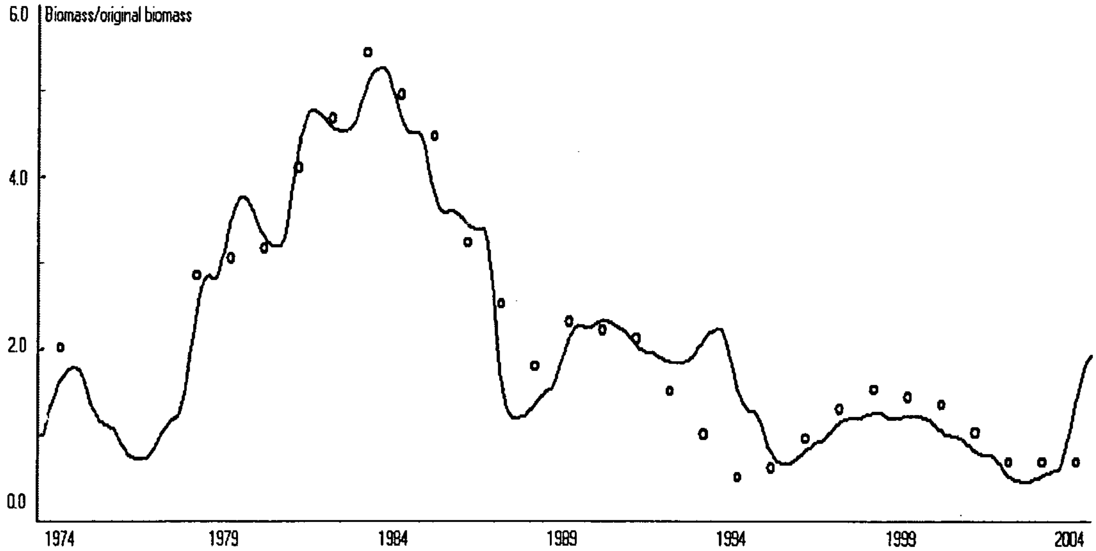

Figure 14. A representative run (screen-shot) from Ecosim for the upper Gulf of California/Colorado River Delta model displaying the predicted biomasses of shrimp (line) and biomasses obtained from surveys (dots) in the upper Gulf from 1978-2003 (see text for references).

2.4.3. Ecosystem dynamics.

There are many ways to model and explore interactions within a food web; in this section, two examples illustrate how the ecosystem role of a single UGC species may be explored using Ecosim (Christensen *et al.*, 2000). The 20-year time period for simulations was chosen simply because it was considered to be of adequate duration to explore emergent changes in the system. Both examples, a simulated removal of top predators and detritus from the mass-balanced model, were used to track the changes produced in the biomass trajectories in the system, an essential step in understanding the biotic interactions and the responses of the components. In many cases, functional groups appeared to reach equilibrium after 20 years, while in other cases, the dynamics of some functional groups appeared to maintain some transient dynamics. The dynamic simulations presented in this section do not include any response to physical or environment factors. Chapter IV

presents an analysis of more complex disturbances in the Colorado River discharge, changes in fishing efforts and climate variability.

2.4.3.1. The impact of sharks.

Figure 15 presents a simulated removal of large sharks (black-tip, *Charcharhinus limbatus*, horn shark, *Heterodontus mexicanus*, and smooth-hound shark, *Rhizoprionodon longurio*) from the 2000 model, resulting in important changes at the top of the food chain in the upper Gulf system. With a reduction of 90% in the biomass of sharks over 20 years, the biomass of totoaba increased by 110%. Similarly, the reduction of mortality imposed by sharks resulted in a growth of 90% in the sea lion population. In the case of vaquita, its biomass trajectory showed a quick recovery of 40% during the first 10 years, reaching 130% of its initial population at the end of the simulation. Conversely, depletion of squids, jack, crabs, sardines, scombrids, (all by less than 40%), is mainly explained by increased mortality from their predators, such as sea lions, dolphins and vaquita.

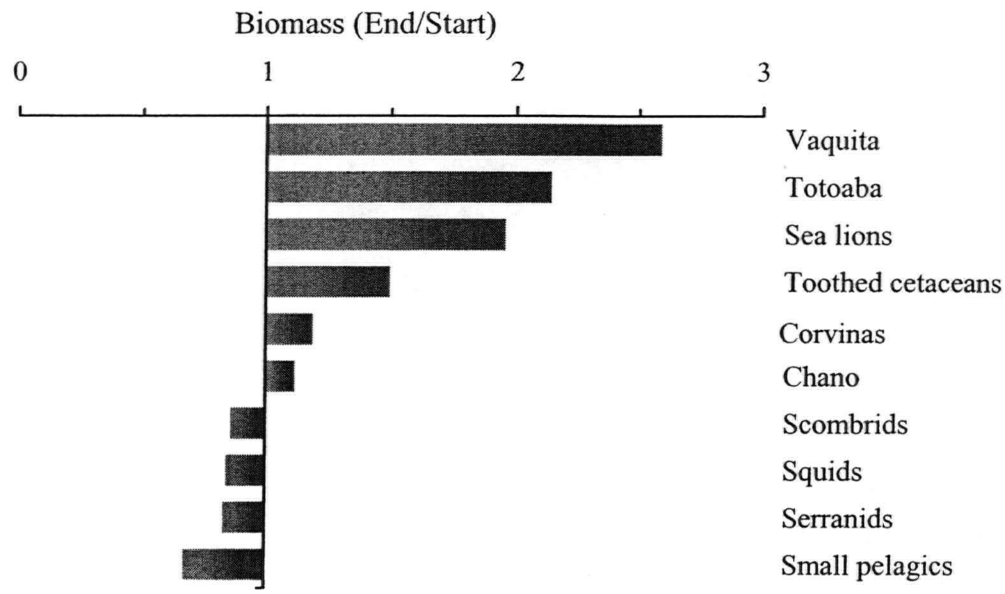

Figure 15. The top ten predicted biomass changes resulting from the gradual reduction of sharks by 90% during a 20-year simulation in the present-day UGC model. The figure presents increases in biomasses of various species such as sea lions, dolphins, vaquita, corvinas and totoaba (right bars) in response to the reduction of predation imposed by sharks. The decline in the biomasses of scombrids, jacks, serranids, and squids is explained as a response to their predators. Overall prey vulnerability was set at 2.5, which represents a mixture of bottom-up and top-down forces structuring the upper Gulf ecosystem.

2.4.3.2. The impact of detritus.

Figure 16 shows a series of potential indirect trophic cascade effects produced by a simulated removal of detritus over 20 years. These effects were perceived in all trophic levels of the system. The biomass of lower trophic level groups such as corvinas, rays, flounders, clams and other benthic invertebrates decreased by 30-60% of their current status. Sea cucumbers declined dramatically to 10% of present population in just 20 years. The ~40% depletion in the biomass of totoaba and vaquita after 20 years is mainly explained by the reduction in the abundance of their prey. This simulated removal of detritus confirmed that the historical detritus and nutrients accumulation from the

Colorado River is a critical attribute in the upper Gulf of California ecosystem, where 43 out of the 50 groups included in the model showed a 20% change in their original biomass.

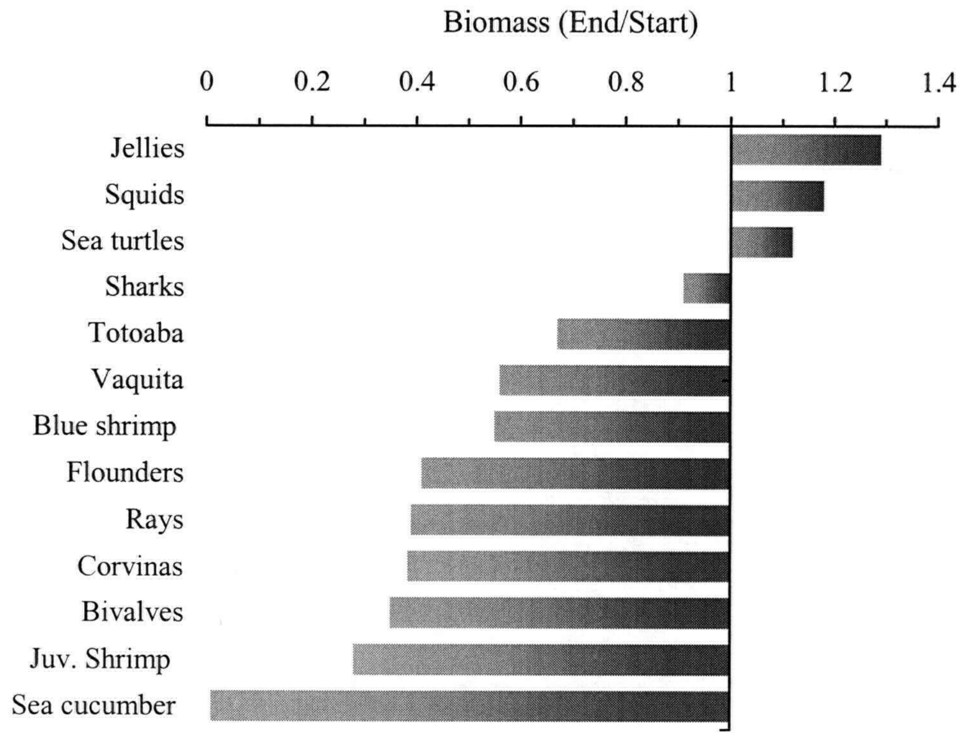

Figure 16. Predicted biomass changes attributable to simulated removal of detritus from the upper Gulf of California model over a period of 20 years. All the groups changed 20 percent or more (43 out of the 50 groups included in the model). Detritus reduction depleted lower trophic level groups, such as sea cucumbers, juvenile shrimps, clams, shrimps, and crabs. Note the dramatic reduction of sea cucumbers after the 20-year simulation. In turn, the decline in the population of sharks, totoaba and vaquita is a result of the decline of their prey.

2.5. Summary.

The first step in answering critical questions about the environmental consequences of the huge dams along the Colorado River was the construction of a dynamic EwE model of present-day conditions. The model describes the interplay of predators, prey, and human fisheries using fifty functional groups (representing 130 species) living in this marine ecosystem. The results presented in this section show that the upper Gulf responds to both top-down and bottom-up changes. They underscore the role of the Colorado River as the principal source of sediment and detritus to the upper Gulf of California.

Understanding the process and interactions within this complex ecosystem, including the role of both low and high trophic level groups and the impact of fishing mortalities, can promote and support plans for conservation and management. Chapter III presents a EwE model that attempts to reconstruct past stages of the upper Gulf ecosystem and capture changes in the structure and form essential to quantify ecological impacts attributable to the diversion of the Colorado River.

Chapter III.

Historical ecosystem models for the upper Gulf of California and Colorado River Delta.

3.1. Historical changes in the upper Gulf of California/Colorado River Delta: lessons from the past.

3.1.1. The delta of yesterday.

The Gulf of California (then named the Vermillion Sea and later, Sea of Cortez), was first described during the sixteen century by Spanish expeditions (e.g. Francisco de Ullóa, 1523). Early explorers reported jaguars, mountain lions, wolves, Cimarron rams, deer, otters and beavers, a legendary abundance of birds, sea turtles, dolphins, whales and hundreds of fish and invertebrate species living in the estuarine and marine habitats which were formed where the Colorado River met the Gulf of California, resulting in the delta of the Colorado River (Knifing 1931, 1932; Sykes, 1937; Osorio-Tafall, 1943; Leopold, 1948). According to the maps, flora and fauna described by Sykes (1937) and Osorio-Tafall (1943), these pristine conditions continued until the twentieth century. As much as 70% of the Colorado River's silt load was carried to the upper Gulf (Thompson, 1968; Luecke *et al.*, 1999). The annual overflows of the Colorado fertilized the waters and soils of the delta. In the 1870s, extensive steam navigation was developed for the commerce of cotton and sugar (Shipek, 1965). The delta's richness is further increased by the tidal action of 5m on average (up to 10 m, Lavín 1999), an unusually high ebb and flow that used to extend the tidal estuary up to 50 km upriver (Luecke *et al.*, 1999).

The delta of the Colorado, referred to as a "jaguar-infested jungle" by Aldo Leopold in the 1920s (Leopold, 1949), once covered more than 7,700 km^2 with water with inputs of 7,000 m^3s^{-1} and a transport of sediments at a rate that resulted in up to 50 m thick deposits in some areas (Varady *et al.,* 2001). The sediment load from the Colorado has been estimated in the order of 160 x 10^6 t/year (van Andel, 1964), producing during the

Quaternary a cone of sediments of more than 7,700 km^2 at the mouth of the river (Carraquiry and Sánchez, 1999). These high rates of sediment discharge interacted with the strong tidal regimen to create tidal bores (>3m) that more than once have sunk large ships operating in the upper Gulf, with the loss of several human lives (Sykes, 1937). Since the Spanish explorers, navigating the mouth of the Colorado and its channels, has been described as 'dangerous' because of the strength and magnitude of the spring tides and the tidal bores (Sykes, 1937; Osorio-Tafall, 1943; Leopold, 1949). Today, tidal bores are still a feature of the region, but observers report maximum heights of about 1 m (Carbajal *et al.*, 1997). The interruption of the sediment discharge for almost a century appears to have suspended the natural construction and development of the Colorado delta (Meckel, 1975). Sediments deposited before the diversion of the Colorado River are now re-used by the tides, suggesting that this deltaic system is going through an erosional stage (Carraquiry and Sánchez, 1999).

Humans first attempted to control the natural flow of the Colorado River during the late 1800s, shortly after, in 1922, the first Colorado River Compact was signed. Twelve years later, the colossal Hoover Dam was completed and started to store water, resulting in the formation of Lake Mead. The conclusion of the Glenn Canyon Dam in 1960 was responsible for a 96% reduction of the original river flow (Fig. 2). Since then, the fresh water delivered to the upper Gulf has been about 4% of that at the beginning of the century (Lavín, 1999). Except for years with strong precipitation events, such as 'El Niño', not a single drop reaches the upper Gulf of California (Vandivere and Vorster, 1984). Figure 18 shows the discharges of the Colorado at the Southerly International Boundary (SIB) and an undepleted discharge estimate by Cohen *et al* (2001), revealing the magnitude of the water impounded and lost by the upper Gulf ecosystem by the series of dams along the Colorado. Although the Colorado delta can be influenced by a natural process (climatic oceanographic, geotectonic), the water diverted by the dams is now the major factor affecting the delta (Carraquiry and Sánchez, 1999).

Unfortunately, as the water of the Colorado River was diverted, the future of native people living in the delta and along the Colorado was ignored and they were left out of discussions of the management plans. There are several Indian communities that have lived, hunted and fished in the Colorado waters for centuries (Chemehuevis, Havasupais, Hualapais, Southern Paiutes, Southern Ute, Yumas, Mohave, Navajos and Cocopá). The Cocopás subsisted by fishing and farming in the margins and delta of the Colorado River before colonization. For Cocapás, the core zone of the present Biosphere Reserve represents the territory where their culture and fishing tradition (Bowen, 2004) developed over thousands of years. Today, they are the only people allowed by the Mexican government to fish in the core area of the Biosphere Reserve and approximately 225 out of the 700 Cocapás in the delta fish in the upper Gulf (Ballinas, 2002): 80% of their fishing effort is concentrated on the gulf corvina (*Cynoscion othonopterus),* resulting in earnings of $2,000 to $3,000 per fisher/season (Moreno-Mena and Suárez-Sánchez, 2002). In 2002, the CNDH (The National Commission of Human Rights) recommend to SAGARPA (Agricultural and Fisheries Secretariat, Mexico) a more active participation of Cocapás in social development and policies in the upper gulf (Ballinas, 2002).

3.1.2. The delta of today.

With more than 20 dams, the Colorado River Basin is now called 'the world's largest plumbing system' (Fradkin, 1981) and it is considered to be one of the most highly regulated rivers in the world (Andrews, 1991). Like many other large river deltas, such as the Amazon (Barthem *et al.,* 1995) or the Mississippi (Arthington and Welcomme, 1995), river impoundment of the Colorado for a century has had devastating effects not only in the wetlands, but also in the estuarine and marine habitats of the upper Gulf (Briggs and Cornelius, 1998; Brusca *et al* 2001; Glenn *et al*., 2001).

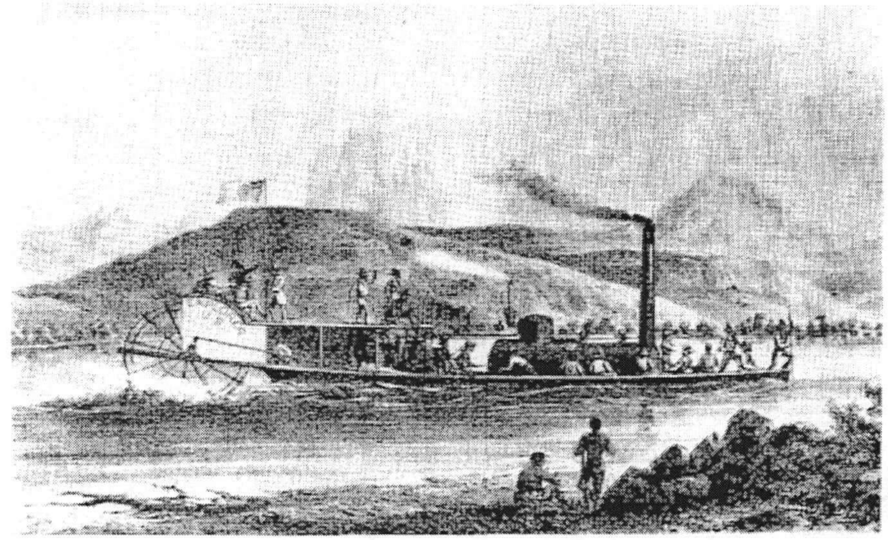

Figure 17. Painting from 1845 of a steamer crossing the Colorado Delta; at the bottom two people from the indigenous Cocapás community are represented as the first habitants of the region (reproduced from Sykes, 1937). From 1850 to the 1900s the Delta supported an intense commerce of cotton and sugar transported by steamers up river as far as Yuma.

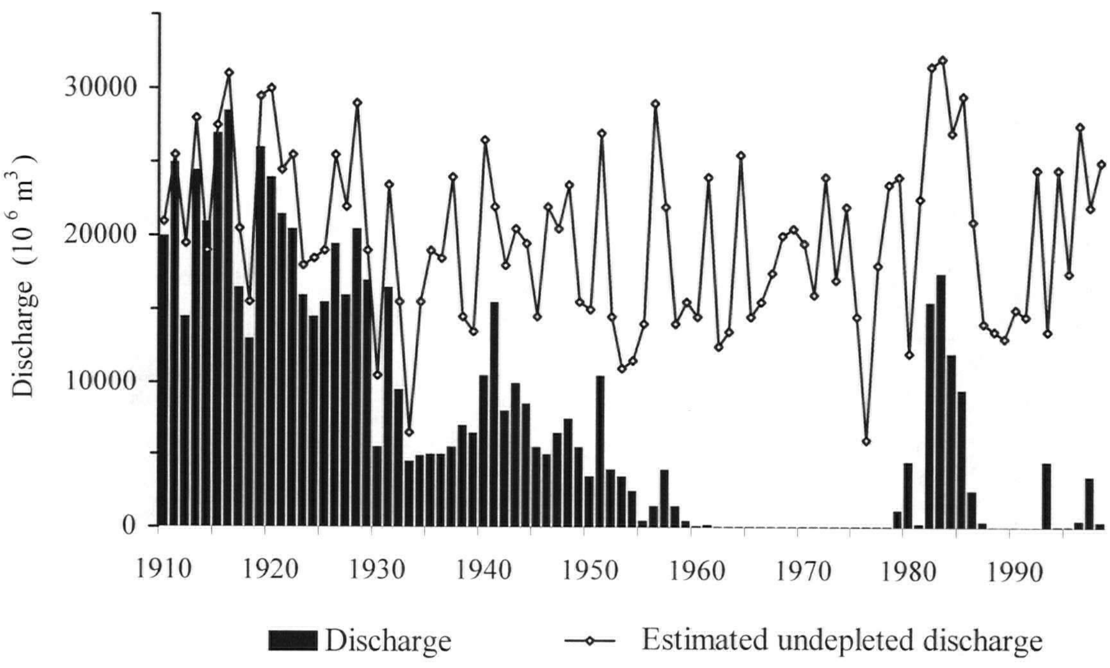

Figure 18. Colorado River discharge at the southerly International Boundary from 1910-1998. The black bars represent the recorded river discharge and the line reflects the undepleted discharge of the Colorado estimated by Cohen *et al.* (2001).

During the twentieth century, Colorado water reaching the Gulf was reduced by more than 95%, from an annual average of 29 x 10^9 m^3 from 1896 to 1921 (Fradkin, 1981) to an annual average of 2.6 x 10^9 m^3 from 1984 to 1999 (Glenn *et al.*, 1999). Some of the changes produced in the upper Gulf and its delta by the reduction of Colorado water are discussed next:

1. An erosion process has begun in the region, and like other river deltas at risk, such as the Nile (Stanley and Warne, 1993), the Colorado delta has actually begun to decrease in size (Carraquiry, 1999).

2. The combination of river impoundment and diversions has reduced delta wetlands to about 5% of their original extent (Brigghs and Cornelius, 1998), which have been reduced to about 5% of their original extent. Native forests of cottonwood and willow have yielded to sand and mudflats dominated by the non-native salt cedar, decreasing the habitat value of the riparian forest (Briggs and Cornelius, 1997; Luecke *et al.*, 1999).

3. Much of the upper delta has been converted to irrigate farmland, levees and channels that have changed the area significantly (Luecke *et al.*, 1999; Brusca *et al.*, 2001).

4. An alteration in the hydrography and currents of estuarine and marine habitats in the upper Gulf has occurred (Carbajal *et al.*, 1997; Lavín and Sánchez, 1999).

5. An increase of salinity in the lower delta has inhibited agriculture activity. The diversion of freshwater combined with the high evaporation typical of the upper Gulf has produced a permanent increase of salinity in the region, with average values changing from 23-35 before dams to current salinities that are typically in the range of 35-45 (Lavín *et al.*, 1998; Lavín, 1999). Today, the upper Gulf is a negative estuary, where salinity increases toward the mouth of the river; this occurs throughout the year, despite the seasonally reversing temperature gradient (Lavín *et al.*, 1998). Figure 19

presents a comparison between the current salinity in the upper Gulf and that estimated by Carbajal *et al* (1997) using a constant discharge of freshwater of 2000 m^3/s.

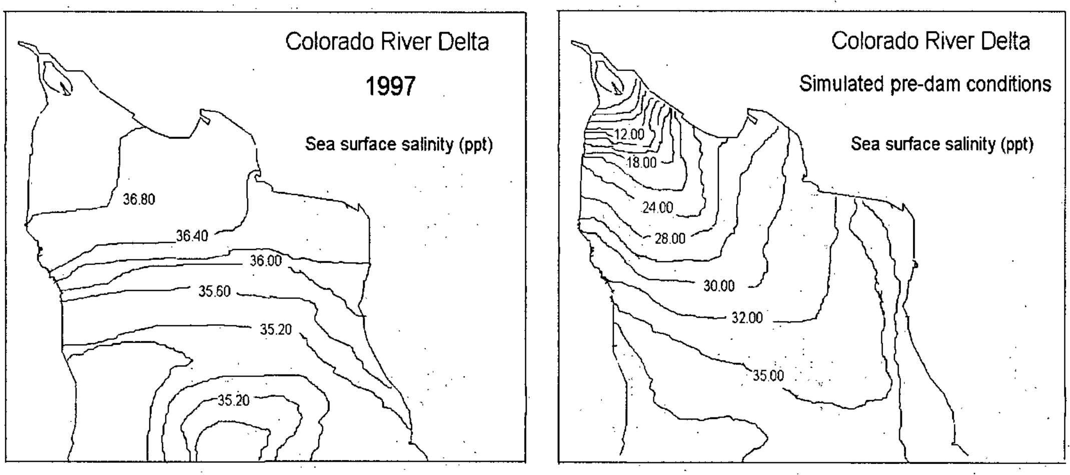

Figure 19. Sea surface salinity values in the upper Gulf of California. Left panel shows the surface salinity (0-10 m) under present conditions. Right shows salinity distribution simulated using a constant discharge of freshwater of 2000 m^3/s (Carbajal *et al.* 1997). Since the construction of the Hoover Dam in 1935, the hydrography of this region has been profoundly modified, and today the upper Gulf is an inverse estuarine system (with higher salinities in the mouth of the river).

3.1.3. A changing fauna.

The increase in salinity has degraded both the delta conditions that are critical for spawning and the nursery grounds of hundred of species, including invertebrates, fish, reptiles, marine mammals and birds that use the delta and its marine zone. Several examples illustrate the importance of the freshwater, sediments and nutrients delivered by the Colorado River:

1. The bivalve mollusk *Mulina colorandensis* was once the most abundant species of clam inhabiting the delta, but today, only a small relict population survives near the river's mouth. Kowaleski *et al.* (1996) estimated that approximately 500 billion shells

make up the Delta's beaches, where 85-95% of the shells are from this species (Kowaleski *et al.*, 2000; Rodriguez *et al.*, 2001; Flessa *et al.*, 2001). The population of these bivalves has been reduced from 50 clams/m^2 (before dam construction) to approximately 3 clams/m^2 in 2000 (Rodriguez *et al.* 2001). This dramatic change is mainly explained by the change in salinity discussed above (Flessa *et al.*, 2001).

1. Blue shrimp catches (*Litopenaeus stylirostris*) and their post-larvae abundances are positively correlated ($P<0.05$) with the rate of freshwater delivered by the Colorado, (Galindo-Bect and Glenn, 2000; Aragón-Noriega and Calderón-Aguilera, 2000; Calderón-Aguilera *et al.*, 2002). Lower salinity would increase the nursery area of this species, increasing the survival of its early life stages (Galindo-Bect and Glenn, 2000). A parallel circumstance has been reported in the southwestern Gulf of Mexico by Garcia (1991), where the recruitment of white shrimp (*Peneaus setaceous*) was positively correlated with river discharges, resulting in an expansion in estuarine nursery habitat. Figure 20 shows the important role of the Colorado River discharge in the production of blue shrimps in the upper Gulf.

2. It is remarkable that the Gulf corvina (*Cynoscion othonopterus*), an endemic Gulf of California fish that had not been seen in the upper gulf for 20 years (1970-90), returned in large numbers to the delta after the floods of El Niño 1992-93 (Zengel *et al.*, 1995; Cudney-Bueno and Turk, 1998). Since then, an important fishery was established in the region (Fig 21). Figure 22 shows a photograph taken in 1934 in Puerto Peñasco showing the abundance of Gulf corvina and totoaba in the waters of the upper Gulf of California (Hendrickson, 1979).

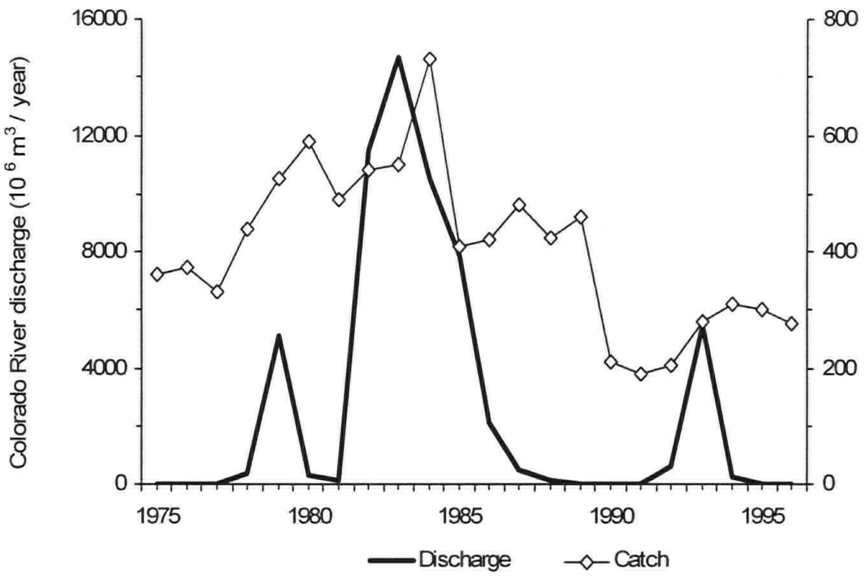

Figure 20. Blue shrimp (*Litopenaeus stylirostris*) landings were significantly correlated ($P<0.05$) with Colorado River discharge in the same year. This relationship is explained by an increase of the nursery area and survival of larvae as result of the freshwater input, revealing the importance of the Colorado River in the ecology and economy of the upper Gulf of California. Data from Galindo-Bect and Glenn (2000).

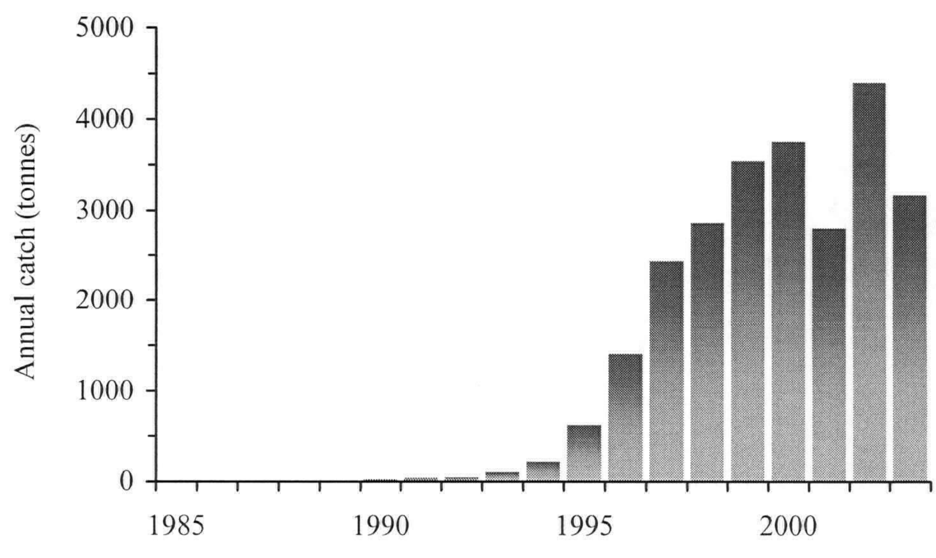

Figure 21. Historical landings of the Gulf corvina (*Cynoscion othonopterus*) in the upper Gulf of California. This species vanished in the upper Gulf for more than 40 years until it returned in early 1990s, activating a new fishery in the region.

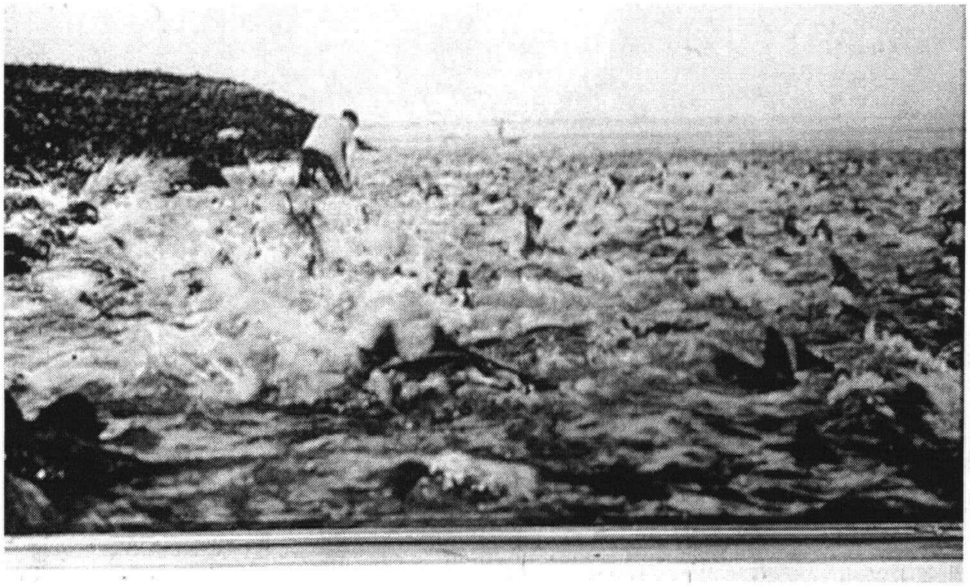

Figure 22. Photo of Puerto Peñasco, 1934 including Gulf corvinas (*C. othonopterus*) and totoaba (*Totoaba macdonaldi*) taken by L.M. Huey (1934) and published by Hendrickson (1973).

These cases illustrate that the Colorado River once played a major role not only supplying sediments, nutrients and organic matter, but also providing low-salinity nursery areas for larval shrimps and fish fry where euryhaline predators could not penetrate. Moreover, uncontrolled fisheries have brought several endemic species such as the giant Gulf Croaker or totoaba and the vaquita porpoise near to extinction (Cisneros-Mata *et al.*, 1995; Román-Rodríguez and Hammann. 1997; Jaramillo-Legorreta, 1999; D'Agrosa *et al.*, 2000); however, the role of increased salinity in their key habitats is unknown (Glenn *et al.*, 2001). Figure 23 displays some photos taken in San Felipe from 1926 to 1957 showing that, in the past, the upper Gulf was the home of 100 kg totoaba; today these colossal totoaba are gone.

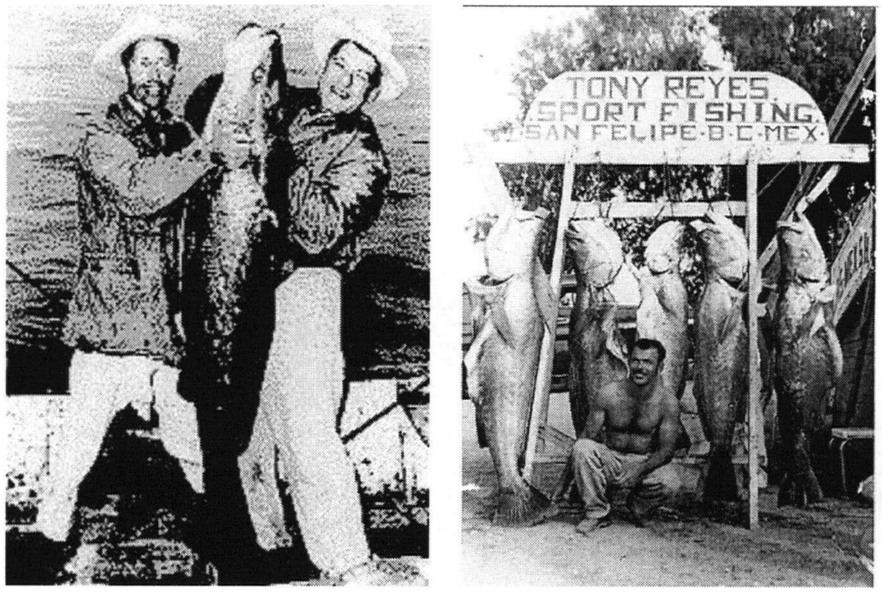

Figure 23. Totoabas of nearly 100 kg caught in San Felipe the 1940s (left) and 1954 (right), confirming that huge totoabas were formerly common in the upper Gulf; today these colossal totoabas have vanished. Photos courtesy of Desert Fishes Council (*www.desertfishes.org*).

3.2. Oral inputs to UGC ecosystem reconstructions: Results from interviews fishers of the UGC during May-June 2003.

As explained in Chapter I, the modelling work in this thesis uses the 'Back to the Future' approach that integrates knowledge of ecological, economic and social fields to reconstruct past stages of marine ecosystems. This interdisciplinary methodology may help to answer new questions about what an ecosystem was like before large commercial fisheries or any other human stress factors (i.e., dam construction). In order to understand changes occurring throughout time, the BTF approach incorporates TEK and LEK (Traditional and Local Environmental Knowledge) that provides information about the use of natural resources by the local people of the ecosystem modeled (Pitcher *et al.*, 2005). This thesis addresses the participation of local fishers' knowledge (hereafter termed LFK) from the communities of the upper Gulf as a method to promote participation and knowledge in the enhancement of ecosystem models and the resulting potential plans for conservation and restoration.

The local ecological knowledge concept can be defined as the knowledge held by a specific group of people about their local ecosystem (Nygren, 1999). Although it is challenging to incorporate TEK into scientific analysis (Johannes *et al.* 2001), there are several studies of terrestrial ecosystems that have combined scientific data with local and traditional knowledge in order to make better decisions in sustainable resource management (Nazarea-Sandoval, 1995; Berkes and Folke, 1998; Berkes *et al.*, 2000, Huntington, 2000; Berkes *et al.*, 2003). Only a few studies have addressed the potential existence and use of such knowledge in marine ecosystems. The BTF approach has proved the value of LEK in the reconstruction of marine ecosystems around the world (Western and Eastern coasts of Canada and Hong-Kong; Pitcher *et al.* 2005), providing critical insights of the past states of these systems. It is important to keep in mind that LEK is not a result of a systematic scientific study; its strength is in a lengthy series of local observations (Folke *et al.*, 2003).

The environmental knowledge of fishers could be very useful in countries such as Mexico, where historical records of landings and abundances before the 1970s are few or absent. The potential use of fishers' perceptions and historical anecdotes has helped to quantify important declines of sharks, turtles and big groupers in the central Gulf of California over the past 60 years (Sáenz-Arroyo *et al.*, 2005).

In this thesis, significant effort has been made to incorporate the perception, historical anecdotes and environmental knowledge from fishers into the building of trophic models of former states of this rich marine ecosystem during the past 60 years. The LFK survey (Appendix 5) had two purposes: (1) to gain information about the fishers' perception of past states of the UGC, including losses of abundances, diversity and trophic structure by fishing and effects of the Colorado River Diversion; and (2) to obtain estimates of relative past abundances of non-commercial species, a critical aspect for the building of past trophic models of the UGC.

3.2.1. Shifting baselines syndrome.

An important element to consider in the LFK analysis is how the perception of the health of the upper Gulf of California has changed throughout generations of fishing or by the presence of the water diverted from the Colorado River. These changes in the perception of the state of any environment from generation to generation have been described as 'Shifting Environmental Baselines' by Pauly (1995). Also, this phenomenon has been reported not just for fisheries, but also in social sectors (www.shiftinglines.org), explaining why people could be so tolerant of depletion of resources or increasing violence, respectively.

Important evidence of shifting environmental baselines has been described in the central Gulf of California by Sáenz-Arroyo *et al.* (2005), where old fishers mentioned that 85% of the species had been depleted compared to just 10% by young fishers. In addition, perceived maximum size of the largest Gulf grouper caught (*Mycteroperca jordani*) was significantly different among the three generations of fishers, ranging from 84 kg (mentioned by old fishers) to 63 kg reported by young fishers (Sáenz-Arroyo *et al.*, 2005). Comparisons of the catch records of the tuna boats in the Gulf of Mexico with recent surveys also found that the current population of the oceanic white tip shark (*Carcharhinus longimanus*) is less than 1% of the density recorded by tuna fishers in the 1950s (Baum and Myers, 2004).

A similar trend of depletion has been well documented for totoaba in the upper Gulf of California, where more than five decades of exploitation resulted in the collapse of its fishery in the late 1970s and current risk of extinction (Cisneros-Mata *et al.*, 1995; Román-Rodríguez and Hammann. 1997). As a result of the intense fishing pressure imposed since the 1930s on totoaba, the average size of this species was apparently reduced as could be seen in the photo archives kept in San Felipe, Baja California where totoaba of 170-180 cm in length and more than 100 kg were landed in the Port from the 1920s to the 1950s. This range of size contrasts greatly with the largest totoaba of only a

60-80 cm length caught in the 1980s as the best catch possible in the area (announced in tourist promotional of San Felipe, www.mexfish.com). This drastic decline in the average size of totoaba documented through historical archives is shown in figure 24. The following paragraphs present anecdotal evidence from fisher interviews that supports the change in the perception of the environmental degradation of the UGC over three generations. It is particularly important to identify baseline shift in countries such as Mexico, where approximately 65% of the population is under 30 years of age (INEGI 2002), and the perception of previous health, richness and diversity of their environment is not fully visualized or understood, resulting in a society that tolerates the loss of biodiversity and which does not appreciate the conservation efforts that most be taken in order to protect or restore their ecosystems.

Figure 24. Photo archives of totoaba landed in San Felipe in 1926 (left), 1956 (centre) and 1990 (right), where a reduction of abundances and mean size of this species has been observed after 60 years of intense exploitation. This dramatic change in size was used as preliminary evidence to explore the phenomenon of shifting baselines acting in the upper Gulf of California (see text for details). The left and centre photographs are courtesy of www.sanfelipe.com.mx, and the right photo was taken by Malt Quilter (1990; courtesy of www.mexfish.com).

The study area for the LFK survey was the three fishing ports of the upper Gulf of California: San Felipe (Baja California), Puerto Peñasco and Golfo de Santa Clara (Sonora). Data were collected applying semi-structured interviews (Huntington, 2000) with direct verbal interaction with the fishers during the field trip from April 17th to May

20th of 2003. The questionnaire was designed to gain information about the resources, abundances, gear and fishing sites in the region, based on the memory of fishers of different age groups. Because the fishers' use of common names for fish was different among the villages, the interview included flash cards with 55 pictures and common names of the principal species of sea mammals, birds, commercial and non commercial fish, sharks, shrimps and crustaceans reported to live in the area. The LFK questions covered the following aspects (Appendix 5 presents the interview in its English translation):

- Personal information (name, age, date, location).
- Fishing experience.
- Fishing areas and seasons for main target species.
- Estimation of largest animal caught (just for totoaba, sharks and corvinas).
- Fishing gear.
- Percentages of discards.
- Estimations of illegal and unreported fishing.
- Past abundances by decades from 1950 to 1990 for the major groups considered in the model.
- Possibility of local extinctions.
- Perspective of their future as fishers.
- Effect of the water diversion from the Colorado River.
- Impact of the Biosphere Reserve on the upper Gulf of California.

Interviewees were selected by snowball sampling (Berg, 2001), a method that relies on referrals from initial subjects to generate additional subjects. This method, where individuals are selected from the population in a nonrandom manner, was appropriate because shifting baselines have recently been reported in the Central GoC (Saenz-Arroyo *et al.* 2005). My survey focused on interviewing people who began to fish 40 to 60 years ago in order to obtain information about the last 50 years. The technique of snowball sampling reduces search costs but also reduces the likelihood that the sample will

represent a good cross section from the population (Huntington, 2000). The degree to which the sample differs from the population is also unknown (Wright, 2002).

The LFK database was built from 49 interviews of fishers covering the industrial and small-scale fleets. All the interviews were performed individually and mainly during the afternoon, just after the fishers completed their work and met at the beach to socialize. The location of the interviews was variable; in some cases on the beach, on pangas, on trawlers or in the fishers' homes (Fig. 25). At the beginning of each interview, the BTF concept was explained, emphasizing the need to obtain perceptions of the upper Gulf during the 1950s (just before the completion of the Glenn Canyon Dam in 1960). This resulted in younger fishers suggesting older retired colleagues to interview. They, in turn, introduced me to older fishers in their houses. Figure 26 shows the distribution of age of the fishers interviewed in each of the ports visited.

The information provided by questionnaires along with any additional comments was processed to ensure anonymity, according to the requirements of the Behavioral Research Ethics Board of the University of British Columbia. The interviews lasted between 60 and 90 minutes using paper questionnaires and leaving space for the most relevant phrases, anecdotes and parts. The interviews were conducted in Spanish, and some of the relevant comments were translated into English. This fieldwork and survey were supported by the 'Cecil and Kathleen Morrow Scholarship 2002' awarded to the author in 2003. Also, this field trip followed technical and ethical recommendations proposed by Bunce *et al.* (2000), which suggest that interviews be conducted in a respectful manner and minimize the disruption to people's routines. Following these recommendations, the interviews were conducted in private after the fishers accomplished their activities.

Unfortunately, the native Cocopá community was not interviewed during the fieldwork. They live in a remote area of the San Luis Rio Colorado (Sonora), on a small ranch named 'El Mayor' which is 45 km from the main road to San Felipe, Baja California. No public transport is available and the author was not able to visit the site.

Figure 25. Some of the 49 fishers interviewed in the upper Gulf of California from April 17 to May 20, 2003. The semi-structured interviews took place in the fishers' houses (first picture from the left), pangas (center), trawlers (right), or on the beach (not shown). The questionnaire aimed to record the perception of the resources, abundances, gear and sites of fishing in the region based on the memory of fishers of different ages. This fieldwork was supported by the 'Cecil and Kathleen Morrow Scholarship 2002'.

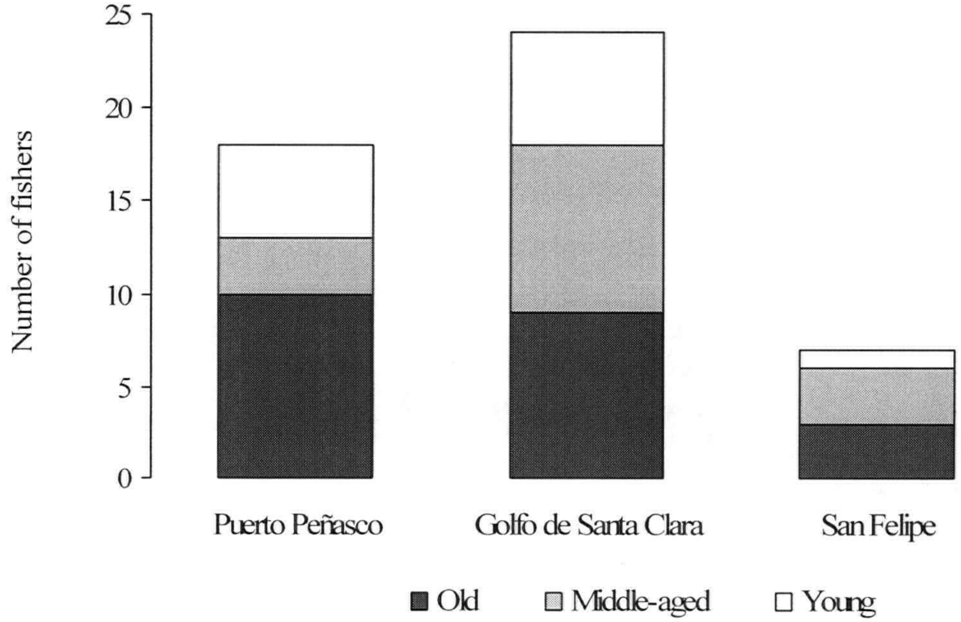

Figure 26. Age distribution of the 49 fishers interviewed in the three main ports of the upper Gulf of California. The three generations of fishers from the three fishing ports were grouped: young (15-30 years old, n = 7), middle-aged (31-55, n = 24) and old (>55, n =18).

3.2.3. Representativeness and Validity

The interviews aimed at gathering detailed information about more than 30 groups of organisms over the past 50 years, but the number and type of interviews can bias results. Each interview is unique and it is possible that, in another situation, the same person could have given slightly different answers (Flick, 1998). In addition, fishers were aware that their opinions would be published in this thesis and possibly in a scientific journal, and therefore, it is possible that they gave 'socially desirable' answers about the Colorado River diversion or increased their estimates of past abundances.

Moreover, results from a small number of interviews can be biased (Yli-Pelkonen and Kohl, 2005), and it is noted that the LFK results from the upper Gulf of California are based on a relatively small number of interviews (n = 49); this is less than 5% of the fishers' population. No recreational, occasional or aboriginal fishers were considered in the LFK interviews, and the results, trends and perspectives expressed by the fishers interviewed may be different from those in other fishing camps. But, although the results may be biased (Berg, 2001) and these issues should be acknowledged for future comparison with results of other interviews in the upper Gulf, most of the trends obtained through the LFK process were shared by fishers from the different fishing camps in the region. Moreover, given the wide experience (more than 1,000 years of combined experience) and deep perspectives of the interviewees on marine resources, the results of the LFK analysis presented in this thesis can at least serve as a preliminary estimate of historical changes in the upper Gulf of California.

3.2.4. Creating time-series of relative abundances

For each of the functional groups of organisms included in the interviews, an index of relative abundance compared to current status was assigned as: increasing (+1), decreasing (-1), or stable (0). These perceptions were ascribed to five decades from 1950

to 2000. The average relative abundance of the main living groups (totoaba, shrimps, corvinas, sharks, vaquita and whales) per decade was calculated from 1950 to 1990 according to a decade's perception of the LFK. All the fishers interviewed were considered 'experts'; therefore, no weighting by experience was applied and the abundances estimated by 'old or expert' or 'young or novice' fishers and their perceptions of abundance were equally averaged.

The relative abundance time series from the interviews was converted into absolute abundance, assuming the same average and amplitude of change as the stock assessment data so that it could be incorporated into the 1950 and 1980 trophic models of the upper gulf. This process was employed only for those species without published references of their past abundances (i.e., sea mammals and non-commercial species). In the case of totoaba, a stock assessment (VPA) was utilized to estimate biomass in the 1950s. In the results presented in this chapter, a comparison is shown between the abundances estimated by LFK and those obtained by stock assessments (VPA) and historical surveys.

3.2.5. Results.

3.2.5.1. Shifting of environmental baselines in the upper Gulf of California.

The majority of fishers interviewed were of the opinion that physical and biological conditions in the upper Gulf have deteriorated. The reasons for these changes were mainly explained by a catastrophic combination of decades of intense fishing and by the elimination of practically all the nutrients delivered by the Colorado River. The LFK analysis also provided a guideline for specific areas that were productive in the past, and that were used for daily fishing, but which are only visited sporadically today.

One of the specific questions asked of the fishers in the LFK analysis focused on their preferred sites for fishing with special emphasis on reduction and changes in catch. According to the opinions of the 49 fishers, a mean number of 4.2 out of the 11 main fishing sites in the UGC have been depleted (Figure 27). The perception of this loss is

different with each generation. For example, old fishers expressed that an average of 5.6 sites (s.d. ± 2.8) has been depleted in the last 50 years; meanwhile, in contrast, middle-age fishers declared an average of 4.1 sites (s.d. ± 2.2) being depleted, and young fishers reported that, on average, only 2.7 UGC fishing sites have been reduced. These results taken from the anecdotes and opinions of three generations of fishers confirms that perspectives on the richness of the UGC have changed. The number of sites depleted that were reported by each of the 49 fishers was plotted in Figure 27. A Kruskal-Wallis test was also applied to evaluate the significance of the differences in the number of fishing areas depleted (Fig. 27). This test proved that there is a significant difference (X^2 = 12.75, d.f.=2, P< 0.005) in the number of depleted sites as reported by three generations of fishers.

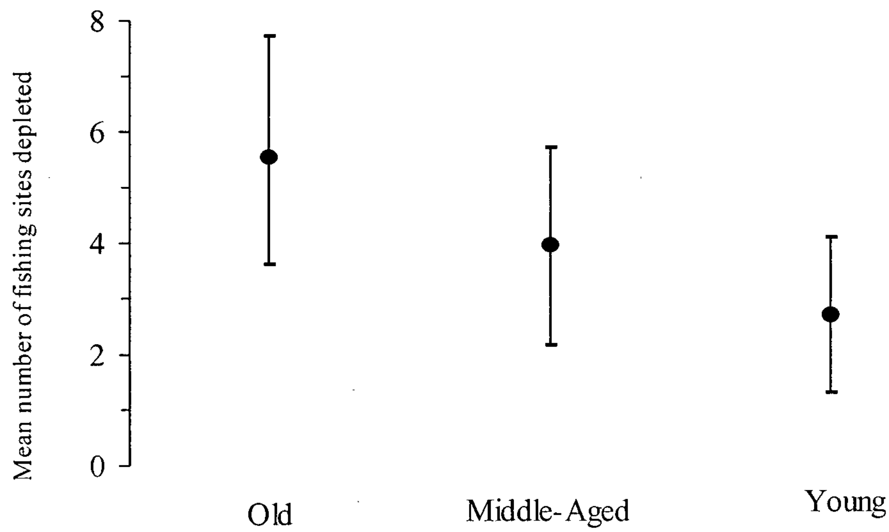

Figure 27. Opinions about the number of fishing areas depleted in the upper Gulf of California from 49 fishers interviews. The difference in the perception of the sites depleted among the three generation of fishers was significant (X^2 = 12.75, d.f.=2, P<0.005), indicating a shifting of ecological baselines in the region. The reduction of the fishing sites was explained by the fishers as a result of decades of overfishing and elimination of nutrients from the Colorado River.

Besides the temporal changes in the number of fishing sites described by the TFK analysis, fishers reported an important spatial change in the distribution of these fishing areas. Most fishers reported a depletion of the fishing sites located in the East coast of the UGC (coast of Sonora), with major declines in the catches from sites like: 'El Borrascoso', 'El Tornillar', 'La Choya', 'La Salina' and 'El Desemboque' (Figure 28). According to the testimony of old and middle-age fishers of Puerto Peñasco and Santa Clara (Sonora), these sites were once rich in totoaba, sharks, sierras and chanos. In contrast, young fishers and middle-age fishers declared that these species are no longer on the East coast of the upper Gulf. In order to catch sharks, chanos and sierras, fishers need to go as far as 30-40 km west, sometimes reaching the other half of the Gulf (Fig. 28). In this case, it is worth mentioning the fishing site named 'El Canalon' (deep Channel), located in the central and deeper waters of the UGC which, according to old and middle-age fishers, was once a very productive site for sharks, specifically from the 1960s to the 1980s (*Sphyrna spp, Mustelus spp, Carcharhinus limbatus*) with biomasses estimated in the range 2-4 t/km^2 in the entire upper Gulf. Numbers appear to have declined significantly, and the site is now used only sporadically for shark fishing.

In contrast, a minor depletion of the fishing sites located in the West coast of the upper Gulf was found by the LFK analysis. According to the perspective of the fishers interviewed, they prefer to fish in sites such as 'Consang Rocks', 'El Coloradito', 'El Moreno' and 'Puertecitos' which are located in the west half of the Gulf (Fig. 28). Fishers of San Felipe (Baja California, West coast of the Gulf), they very often expressed concern about the number of fishers from the East Coast (Puerto Peñasco and Santa Clara) who are fishing for shrimps, sierras and corvinas in "their" waters. Old and some middle-age fishers from San Felipe mentioned that this conflict with the East Coast fishers is relatively 'new', beginning at the end of the 1980s. According to old fishers, they caught totoaba, turtles, sierras, and shrimps within 5-10km of their fishing camps and there was no need to travel or "invade" the fishing sites of other fishing communities, much less travel to the other half of the Gulf (4-6 hrs) in order to fish.

The opinions of the three generations of fishers confirmed that the waters which surround the mouth of the Colorado River (including Montague and Core Islands) are the most productive region of the upper Gulf. They identified this region as an important nursery habitat for the species exploited (i.e. shrimps). Important fishing regions reported by the fishers in the mouth of the Colorado River are: 'El Chinero', 'Punta Sargento', 'El Machorro' and 'Pelicano Island'. However, according to the LFK, even in this small area, productivity has declined in the last 50 years, perhaps due to intense efforts by the Mexican Government which has declared the mouth of the River as a protected area since 1955. The three generations of fishers underscore the importance of nutrients and fresh water delivered by the Colorado River to the survival of larvae and to good catches of blue shrimp close to the mouth of this river.

Another piece of evidence vis-à-vis the shifting of environmental baselines in the upper Gulf revealed by the LFK analysis was the decline in large totoaba caught in the region by the three generation of fishers. Old fishers reported that the biggest totoaba caught during the 1950s ranged from 130-170 cm (average of 156cm ± 19cm); middle-age fishers declared a range from 120-160cm with an average of 141 cm ± 13cm. In contrast, young fishers estimated the biggest totoaba caught was within 110 to 152 cm with a mean of 131 cm ± 19cm. Figure 29 shows the decline in the mean size of totoaba caught by the three generations of fishers during the last 50 years in the UGC. These differences in the mean size of totoabas reported by the three age-groups of fishers were significant (one-way ANOVA, $p<0.05$). The declining trend in the reduction of the mean size of this species, as reported by the LFK, supports the observations made by Cisneros-Mata *et al.* (1995) and Román-Rodríguez and Hammann (1997) i.e. that this reduction in size could be interpreted as a response of the species to several decades of intense exploitation.

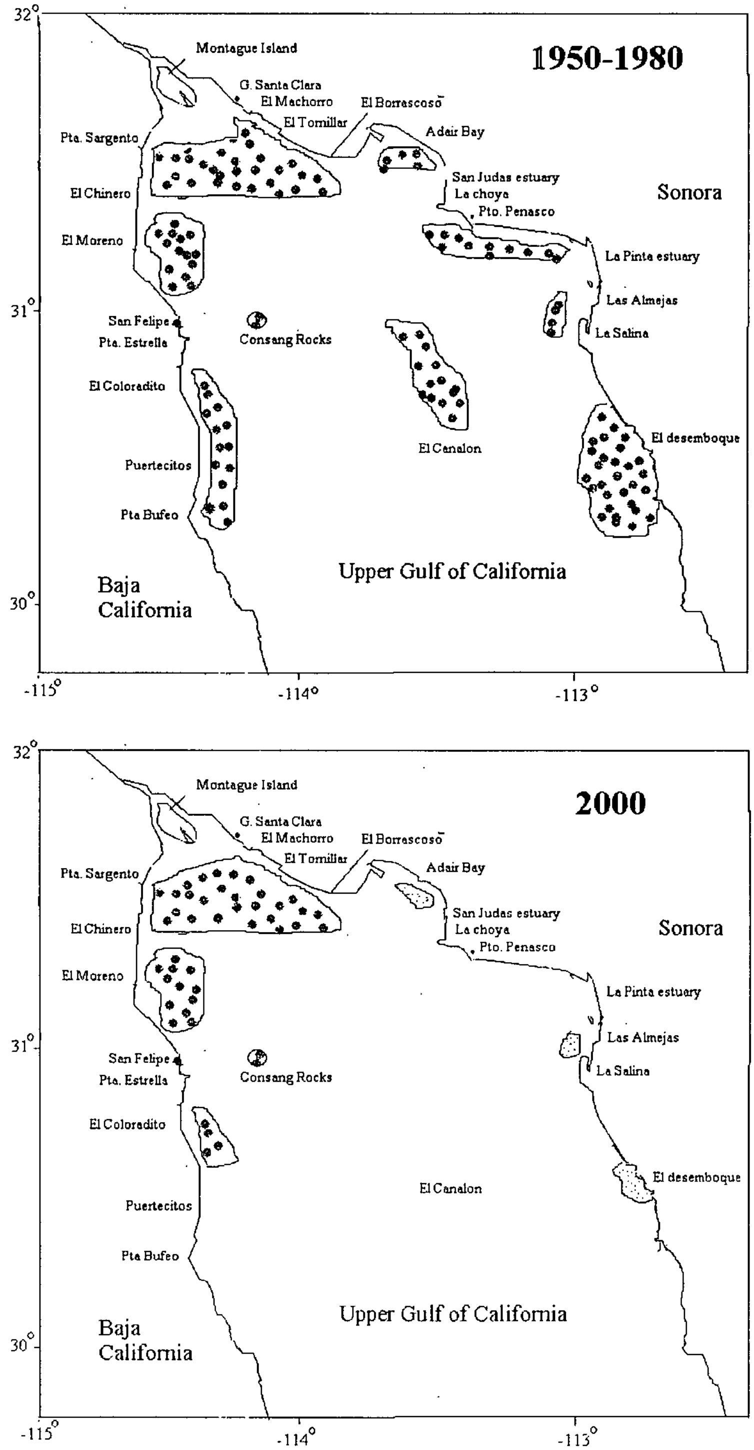

Figure 28. Comparison of the depletion of fishing sites (shaded areas) of the upper Gulf of California from 1950-1980 (upper map) and 2000 (lower map) as described by 49 local fishers. According to their perspective, the east coast of the Gulf has been depleted in the last 50 years, resulting in the best sites for fishing being located on the west coast.

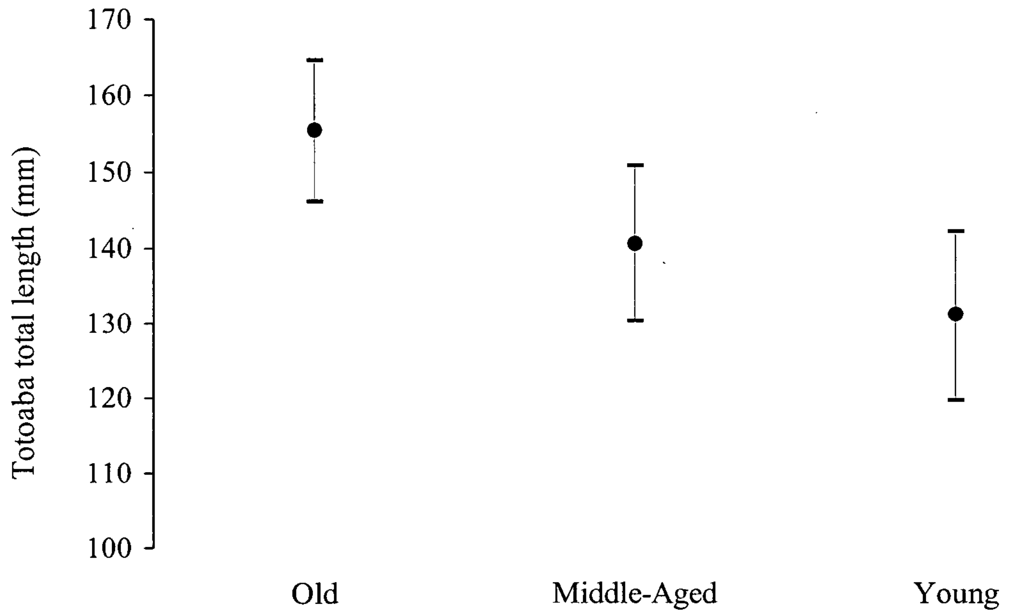

Figure 29. Mean size of the biggest totoaba caught by three generations of fishers as recalled of the upper Gulf of California (n=49). The differences in the mean size of this species reported by the three groups were significant (one-way ANOVA, P<0.05).

The results of the LFK analysis suggest the existence of a shifting of ecological baselines in the upper Gulf. It was perceived that young fishers are very tolerant of the loss and collapse of their fisheries. For example, three major crises were documented in the region when totoaba (late 1970s), sharks (mid 1980s) and shrimps (early 1990s) were depleted to levels that resulted in the collapses of their fisheries. In a general sense, young fishers have the perception that old fishers always exaggerate the richness and diversity of the region and that it is not true that the upper Gulf once supported colossal populations of totoaba, sharks, Pacific sierras and other predators (suggesting equal richness in the abundances of their prey). Such a rapid shift over just a few decades in the perspective of the degradation of the environment is a very important red flag to be considered by both the Mexican government and management authorities if they wish to promote conservation of the region (through courses, seminars or other educational means) and to raise the ecological and economical value of the upper Gulf of California.

3.2.5.2. Estimating past abundances in the upper Gulf of California based on LFK.

Figure 30 shows the estimated relative abundance for eight groups from 1950 to 1990 from information gathered from the 49 fishers interviewed. Most of the groups show a decreasing trend (some groups such as sea lions have been increasing), and according to the LFK results, over the past 60 years, fishery resources have been depleted by 86% in the upper Gulf. The results include several examples of shifting baselines. Older fishers suggested that sea turtles (mainly the green turtle, *Chelonia mydas agassisii*) had populations 6-8 times higher than today's, while younger fishers thought that this species was never really abundant in the upper Gulf, and suggested an average abundance close to 1.5 times higher during 1980 than in 2000. A similar response was apparent when young and middle-age fishers were questioned about the heyday of the totoaba (1940-60); they thought that while totoaba was 2-5 times more abundant and important for the economy of the region, it is was not as abundant as suggested by old fishers, who thought it was up to 20 times higher. Some of the young fishers declared that the old fishers always exaggerate. Sharks provided a parallel observation, where the baseline had clearly shifted across the generations. A remarkable example was attributed to the remembered history of the corvinas; while young fishers had the impression that corvinas are more abundant today than during the 1980s, this point of view contrasts with those who fished during the 1950s and the 1960s. The latter fishers reported that the high abundances of this species created a problem during the gillnet fishery of the totoaba. In contrast, in the case of the vaquita, all the fishers agreed that this species has always been rare. This observation is congruent with results presented by Ortiz (2003), who suggests that the vaquita has always been rarely seen in the upper Gulf and that (1950s) its maximum number was no greater than 2,000-5,000.

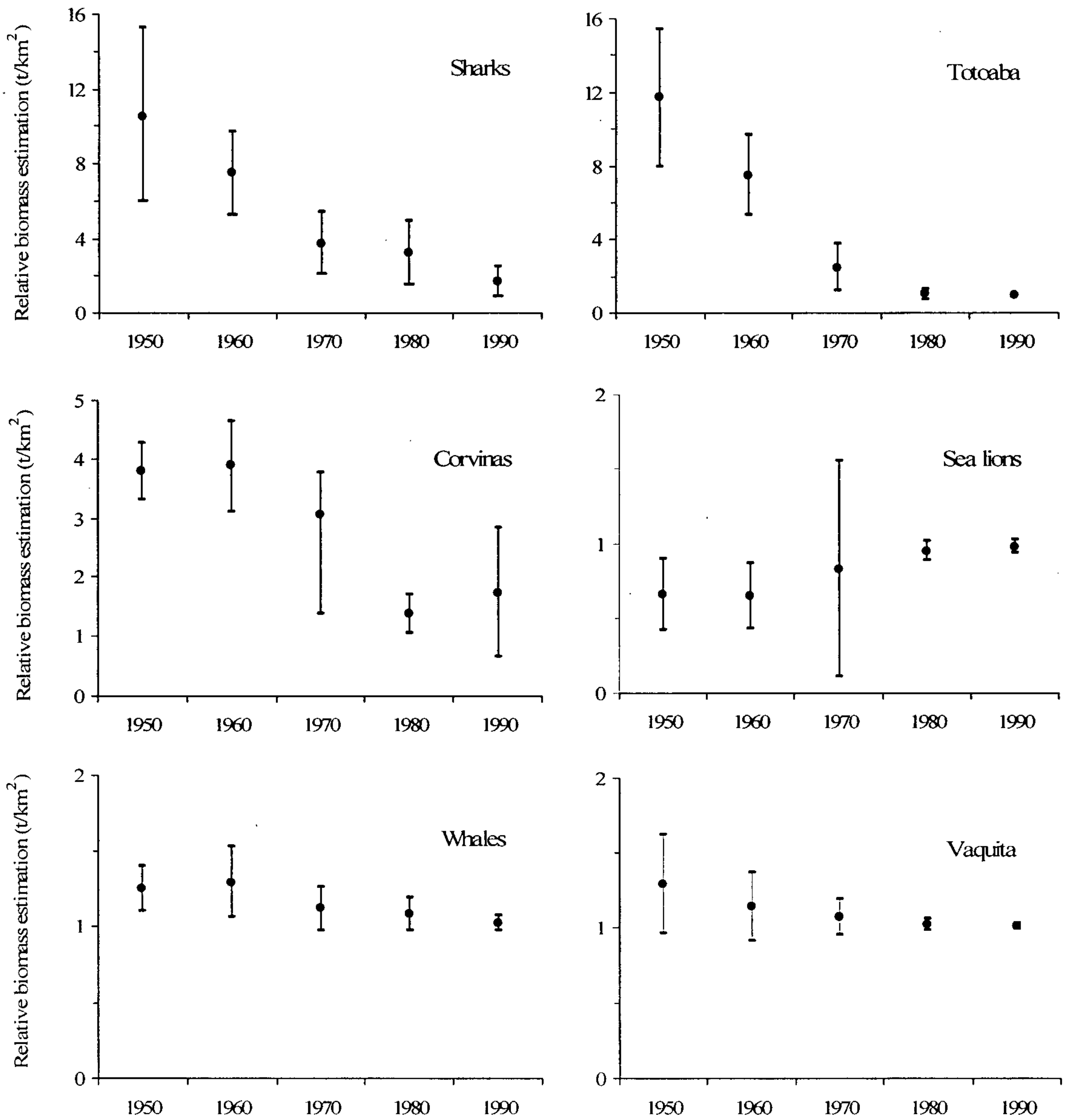

Figure 30. Past abundances (relative to 2000) for eight taxonomic groups living in the upper Gulf of California (black dots). These abundances were estimated from 49 interviews with local fishers of the region. Sample size for 1950 period, 18; 1960, 33; 1970, 36; 1980, 44; 1990, 49 interviews.

It seems that the rich upper Gulf of former times, when it likely supported great abundances of totoaba, corvinas, sharks, turtles and seabirds, lives in the memories of old fishers, but these memories have not traveled across the three generations to today's

young fishers, who do not appreciate the magnitude of the depletion in the region (Sáenz-Arroyo *et al.*, 2005). It is critical for restoration and management that that young fishers and people in Mexico visualize and understand the previous states of their ecosystems.

3.2.5.3. Agreement of LFK with INP records.

Unfortunately, there are no biomass surveys of the region conducted over long periods of time that can be used to compare the past LFK abundances from 1950-2000. In a few cases, such as the totoaba, the extent of the knowledge of this species allows us to estimate its past biomass with a VPA stock assessment. The perceived LFK abundance was converted to an absolute index by scaling the series so that the average and the amplitude of change could be compared with the VPA. Figure 31 shows the LFK trajectory for totoaba and its concordance with VPA biomasses from 1950 to 1975. The agreement between both series was measured using the Spearman Rho nonparametric coefficient of correlation; shows a significant (α=0.05) 82% concordance between the abundances estimated by interviews and the stock assessment. Figure 31 displays a visual agreement between the trends for shark, shrimp and corvina abundances suggested by the fishers and the estimated biomass and landings recorded by INP. The case of corvinas is particularly interesting, where past abundances from LFK suggest an increase since the 1990s. The corvina had been absent in the upper Gulf since the 1970s until its return in large numbers after the El Niño of 1993 (Zengel *et al.*, 1995; Cudney-Bueno and Turk 1998). Figure 31 presents the LFK trend of the abundance of the gulf corvina and its correspondence with the catches recorded since the beginning of the 1990s when its commercial exploitation began. Figure 32 summarizes a Spearman correlation analysis among the trajectories for the LFK and the biomasses and CPUE (kg/boat) reported by INP; the positive correlation for totoaba, corvinas and flounders is statistically significant (α=0.05) while a significant negative trend for flounders indicated that the average fisher's perception contradicts the trend of CPUE from INP data. Overall, there is a satisfactory agreement among the LFK abundances and the reported trajectories of biomasses, but more information is required in both sectors to validate these results.

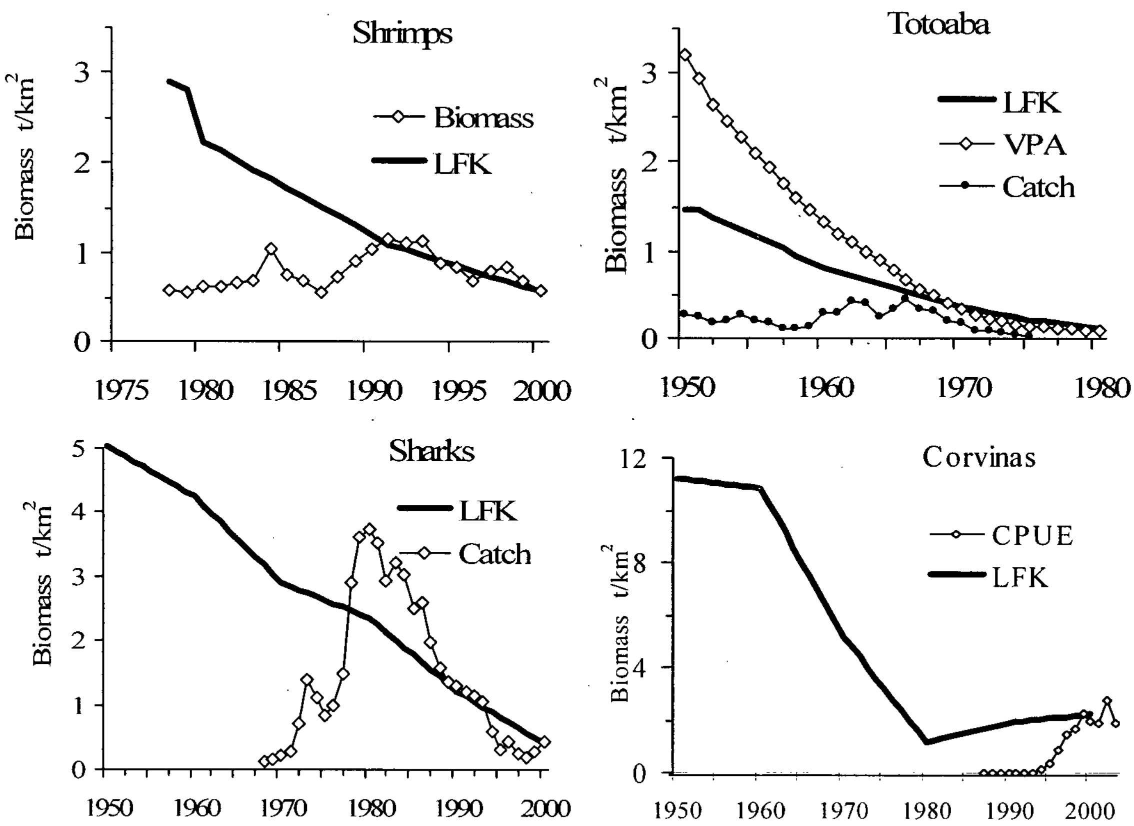

Figure 31. Concordance between relative abundances estimated by the LFK and biomasses estimated by INP surveys (shrimp) or stock assessment (totoaba) from 1950 to 2000. In cases with no absolute biomasses, a relative time-series of biomasses (CPUE, kg/boat) was used for visual agreement. Note the recovery of corvinas described by the fishers and its agreement with the reported return of this species to the upper Gulf after 30 years (Zengel *et al.*, 1995; Cudney-Bueno and Turk 1998).

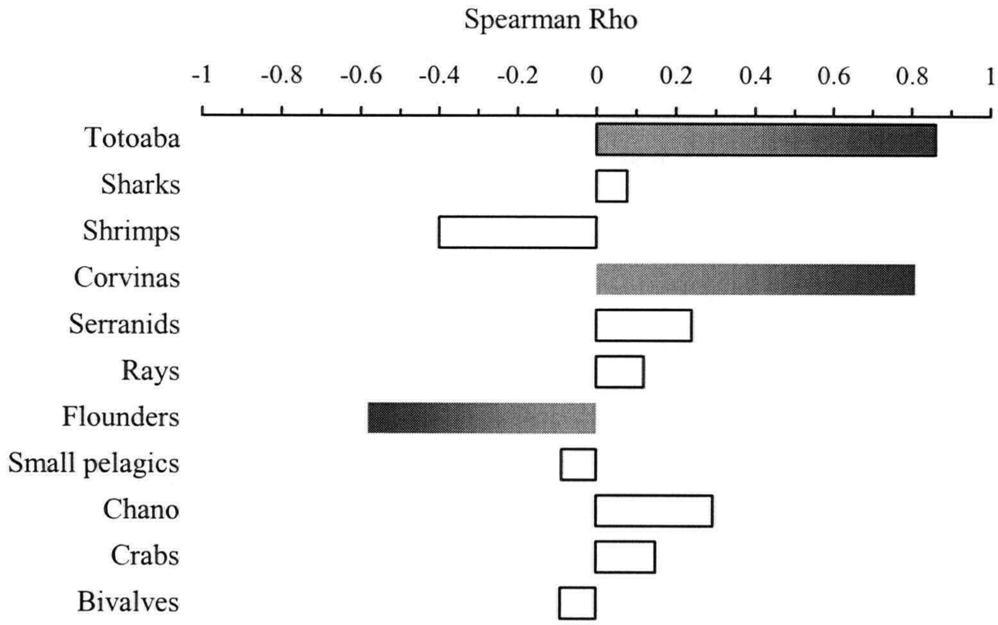

Figure 32. Summary of the outcome of a Spearman correlation analysis among the trajectories of perceived abundance from LFK and the biomasses (shrimps), stock assessment (totoaba) and CPUE (sharks, corvina, serranids, rays, flounders, chano, crabs and bivalves). Only the gray bars are statistically significant (α=0.05).

3.2.5.4. Opinion of the fishers about the freshwater diversion from the Colorado River.

As detailed in Chapter II, the water from the Colorado River has been diverted by consecutive dams since 1934. Analysis of the LFK data shows that the ecological impact of this water reduction is well perceived by the fishers of the upper gulf, with more than 80% considering these dams to have a negative impact on the Mexican ecosystem (Fig. 33). None of the fishers who participated in the LFK survey considered the huge dams along the Colorado River to have had positive effects on the diversity and fisheries of the upper Gulf. Less than 10% interviewed said that the dams have had no effect on productivity. 94% were younger than 55, suggesting again a generational shift of the environmental baselines in the region.

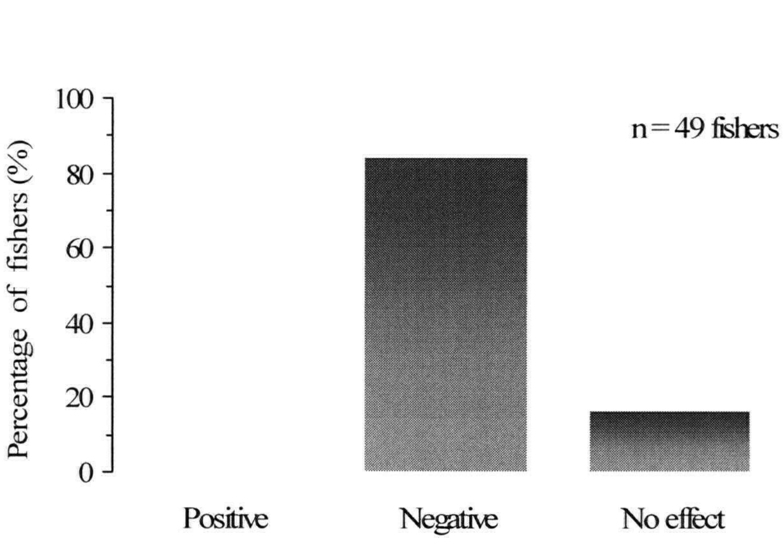

Figure 33. Opinion of 49 fishers from the upper Gulf of California on the impact of the historical water diversion of the Colorado River by U.S. dams.

3.2.5.5. Opinion of the fishers about the future of their fisheries.

The 49 fishers interviewed are negative and pessimistic: more than 70% of them thought that catches will be worse in the future (Fig. 34). Fishers were adamant that their sons not become fishers. Many factors influence this firm and determined answer: corruption among authorities and decision makers, a lot of illegal fishing in the area as there is no real control of the numbers of operating pangas, and low and changing market prices. These views likely reflect considerable problems for fisheries management in the region.

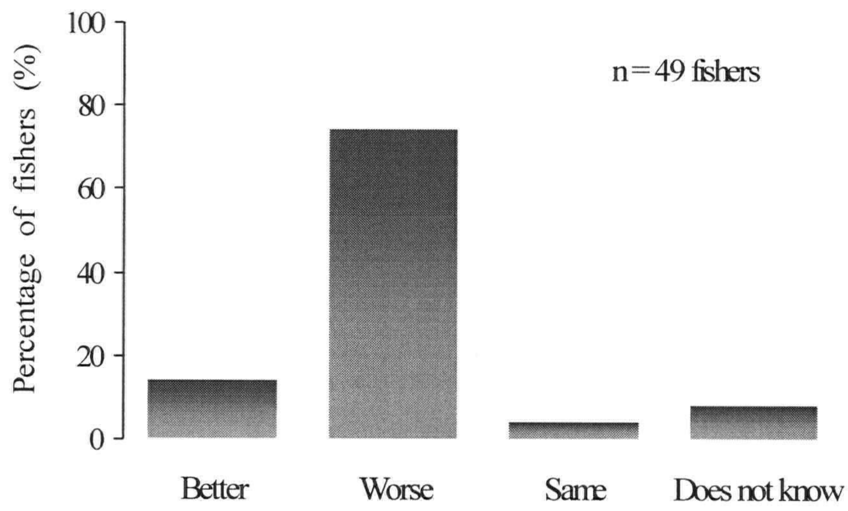

Figure 34. The dismal future of fisheries in the upper Gulf of California, according to 49 fishers living in the region. This pessimism is a reflection of more complex social issues (illegal fishing, corruption and lack of control of fishing effort) as well as economic issues (low and changing market prices).

Another question in my interviews related to possible benefits of the establishment of the Biosphere Reserve in their community. The general perception of this protected area is positive (only 14% of the interviewees declared a negative effect) and fishers from all three communities believed that this reserve has helped the marine resources of this ecosystem.

3.2.5.6. Final remarks.

A recent study of the central section of the Gulf of California reported a shifting of environmental baselines, where for example, old fishers remember an abundance four times greater of the Gulf grouper (*Mycteroperca jordan*) than younger fishers, while only a few young fishers appreciate that large species of sharks, groupers and turtles have ever been abundant in the central GoC (Sáenz-Arroyo *et al.* 2005). The LFK conducted during this thesis confirms the existence of a shifting of ecological baselines phenomenon in the upper section of the Gulf of California.

In the absence of baseline ecological studies of the pre-diversion period, more than a thousand collective years of experience of the 49 fishers interviewed represents a valuable source of information that may be incorporated into quantitative modelling to evaluate the possible impacts of the Colorado dams. The LFK analysis represents the only way (with a few exceptions from the fossil records) to estimate past abundances for many non-commercial species (seabirds, marine mammals, fishes and invertebrates) in the area. Table 7 presents some of the relevant anecdotes captured by the LFK interviews, giving an impression of the past richness of the region and its gradual change over 50 years to a polluted and endangered ecosystem. Overall, this LFK material raises a red flag pointing out that besides the water diversion, there are critical factors such as pollution, corruption and drug traffic. (For example, 367 dolphins, 51 sea lions, 8 whales and more than 200 seabirds died close to San Felipe after consuming NK19, a synthetic cyanide compound used for tracking drugs at night, Azuela de la Cueva *et al.*, 1995). From the fishers' perspectives, the future of the upper Gulf of California will be based on tourism.

Although just two time-series of past abundances described by the fishers significantly correlated to the biomass reported, the overall agreement for the rest of the 19 species analyzed was satisfactory. Hence, the Local Ecological Knowledge from fishers is employed alongside scientific biomass surveys and fishery information to construct, tune and validate the past trophic models for this ecosystem. The following section describes the methodology and results from these models.

Table 7. Some relevant anecdotes from 49 fishers from the upper Gulf of California interviewed from April 17th to May 20th 2003.

Source	Date	Quote
Interview with a 83 year-old fisher from Puerto Peñasco	1950	*"We used to fish totoabas of 120 kg (without head and tail) and today, just 15-18 kg"; " 9 totoabas = 1 ton"; "Sometimes, we used dynamite to fish totoaba...and the rest of the fish (killed) were left floating on the beach"; "20 tonnes of totoaba with just one trough (gillnet) in the Choya region (10 minutes from Puerto Peñasco)"; "None of the fishers work from May to October (no totoaba) and we left to rest the product".*
Interview with a 78 year-old fisher from Puerto Peñasco	1950	*"We used our kitchens to stores totoabas, there was not enough ice in the town"; "Mountains of 10-20 tonnes (up to 6 m in height) of totoaba' heads on the beach...flies were a nightmare, but seabirds (sea gulls and pelicans) ate all that garbage"; "Before (1950s), while we were sleeping, we could hear (nights without moon), the sound of totoabas on the beach...it was beautiful".*
Interview with a 76 year-old fisher from El Golfo of Santa Clara	1950-1960	*"With the running of totoaba, there were orcas entering to the upper Gulf"; "Most of the sharks (around 80%) were caught on the coast, today, we have to travel 20-30 miles"; "No more Canada geese and Monarch butterflies (in the upper Gulf)".*
Interview with a 74 year-old fisher from Puerto Peñasco	1950-1960	*"Before the 1950s; there were Japanese boats hiring people (from Puerto Peñasco) to cut heads and tails of totoabas"; "Also, they (Japanese) used the sea lion meat as bait".*
Interview with a 73 year-old fisher from San Felipe	1955-1960	*"Turtles were sold on the market, in the same way that chicken or pigs"; " Up to 2 tonnes of sharks per trip, 20-30 minutes from the beach (San Felipe)".*
Interview with a 71 year-old fisher from El Golfo of Santa Clara	1950-1960	*"During low tides, we could find large puddles of freshwater with turtles"; "I used to fish easy 15-20 turtles with harpoon at 10m from shoreline"; "Every year during May was possible to fish Marlin for approximately 1.5 months".* Note: no reports were found to support this anecdote.
Interview with a 64 year-old fisher from El Golfo de Santa Clara	1960-1970	*"When the water of the river (Colorado) changed, we started to fish other things (species) such as: rays, chano, corvinas"; "In the 1960s, chano and corvinas tagging in the gillnets were problem for the totoaba fishing, covering the entire net'.*
Interview with a 57 year-old fisher from Puerto Peñasco	1970	*"The water from the Colorado (river) affects the spawning of the shrimp, the water is the food of shrimps"; "In 1970s I caught 1 ton of baqueta (serranid) with 1 tank of gasoline; today I need 3 tanks for 200 kg ".*

Table 7. Continuation.

Source	Date	Quote
Interview with a 45 year-old fisher from San Felipe	1990	*"Sea lions are a problem for the sierra fishing, they eat it, so we have to use a small chinchorro (gillnet) to distract the sea lions".*
Interview with a 42 year-old fisher from Puerto Peñasco	1990	*"We want to obey the law, but anyway, there is corruption. You can buy a tourism permit for $ 500 dollars". "There is no reason to apply for a legal license for fishing, you always can bribe anybody (authorities)"; "Drugs are a horrible problem among the young fishers, I have nothing to envy to this junky generation".*
Interview with a 38 year-old fisher from Puerto Peñasco	1990	*"All the species use the water (from the Colorado River) for breeding and more closed seasons are needed, at least 6-7 months for each product (species)".*
Interview with a 36 year-old fisher from Puerto Peñasco.	1995	*"Tourism is the future, it is 100% secure".*
Interview with a 29 year-old fisher from Puerto Peñasco	1995	*"We fish for necessity, not for pleasure. We don't have life or social insurances, retirement plans or infonhabit (a low rate government loan for buying houses)".*
Interview with a 27 year-old fisher from El Golfo de Santa Clara	1995-2000	*"The floating garbage is a real problem, it scares all the fishes".*
Interview with a 26 year-old fisher from Puerto Peñasco	1995-2000	*"Pollution is affecting and killing everything, there is diesel everywhere"; "Tourism will help us to survive".*

3.3. Ecosystem models of the upper Gulf of California in 1950 and 1980.

3.3.1. Reconstructing the past.

The first step in assessing the impact of Colorado River diversion on the structure and function of the upper Gulf of California was to construct a model of its present state (Chapter II). The original intention was to build a model of the 1900s, prior to Hoover Dam construction in the early 1930's. This proved impractical, as few data for any species or groups, including LFK materials; were available before 1950, so it was decided to build two past models, one from 1950 (based on oceanographic expeditions, fossil records and LFK), and another from 1980 (with more accurate data on biomass and fishing mortalities). The main goal of building the 1950s and 1980s models was to run them forward to the current model (2000) to quantify possible changes in biomasses and dynamics of the species living in the upper Gulf after 50 years of water diversion. The present day mass-balance model described in Chapter II served as a skeleton for building these two past models. As likely past conditions had already been considered with the need to build past models in mind, no functional groups were added and the basic input parameters (B, P/B, Q/B and diets) were modified when documentation was available. The following paragraphs describe the changes implemented.

3.3.2. Modifying P/B and Q/B ratios.

The total mortality (P/B) for several of the model groups (corvinas, cabrillas, chano, hakes, guitarfish, wrasses, crabs, sea cucumbers) was lower in 1980 than in 2000 because they were fished less heavily in 1980 and 1950. However, for a few heavily depleted groups such as totoabas and sharks, the P/B values are lower in 2000 than in 1950 and 1980. Figure 30 indicates the changes made to P/B among the major groups, where positive values (percentages) represent higher fishing pressures in the past and negatives represent an increase in fishing mortality since the 1950s. Full explanations and sources of information employed to calculate P/B values for the 2000 model are in Chapter II.

Not surprisingly, the most significant changes in P/B between 1950 and 2000 related to highly exploited large fish such as sharks, totoaba and serranids (Fig. 35), and species with historical economic commercial values (shrimps). In some cases, such as marine turtles, the LFK revealed that these organisms were heavily fished and often sold in public markets in the region during the 1950s. Mortality imposed by former turtle fishing resulted in a decrease of 35% in the total mortality of sea turtles from 0.272 (1950 model) to 0.20 (2000 model). Conversely, 'Fishing down marine food web' in the Gulf of California (Sala *et al.*, 2004) and changes in the market demand have increased mortality in species that were not exploited before the 1990s (crabs, chanos, corvinas, rays, guitarfish), so that a reduction of their P/B values for the 1950s and 1980s models was required (Fig. 35).

The rate of consumption per unit of biomass per year (Q/B) may have been lower in the past due to the larger individuals present in the populations of the 1950s, and less so in the 1980's. A few small changes in Q/B were also needed in the 1950s model during the balancing process. Figure 36 shows the adjustments of Q/B for the two past models. Overall, the Q/B of only 12 groups out of 50 was modified less than 20%.

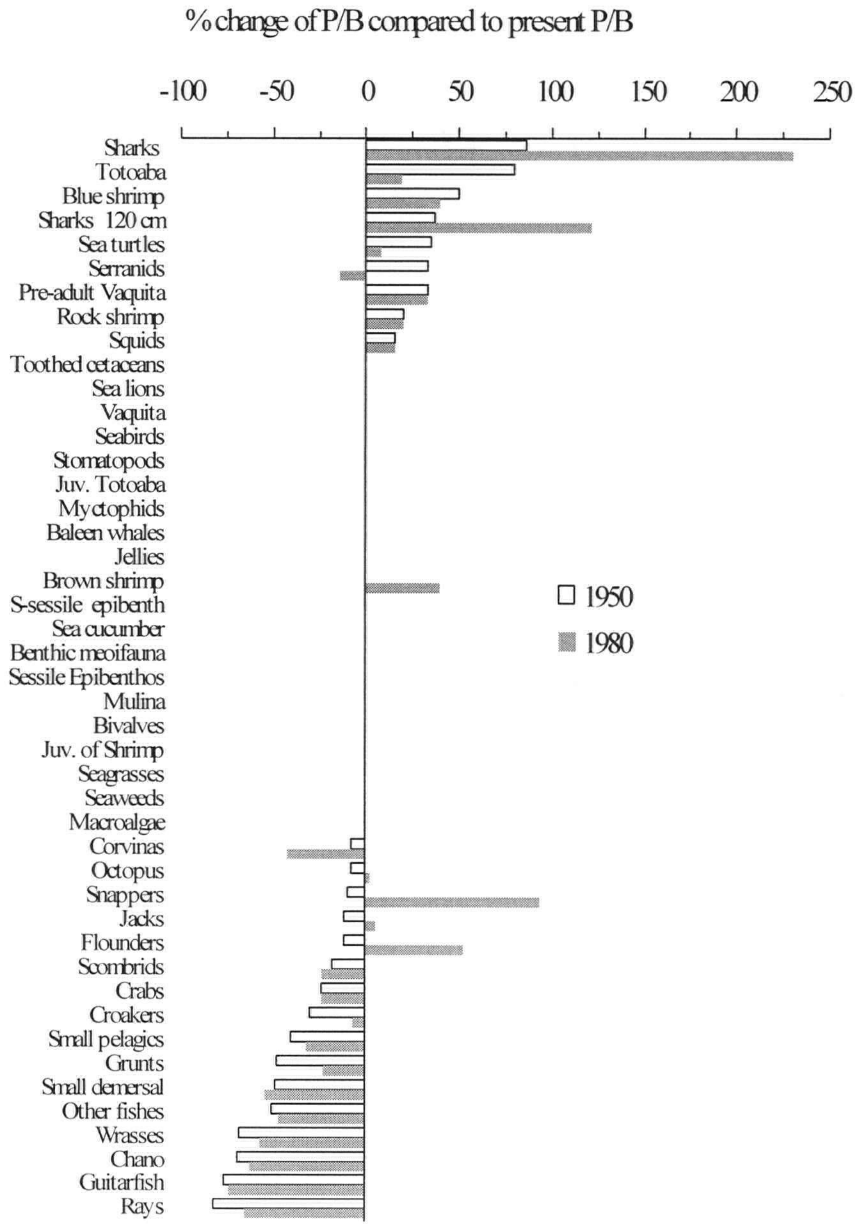

Figure 35. Change in Production to biomass ratio (P/B) of major groups in the upper Gulf of California from 1950 (white bars) and 1980 (grey bars) compared to 2000. Note P/B is equivalent to total mortality (Z).

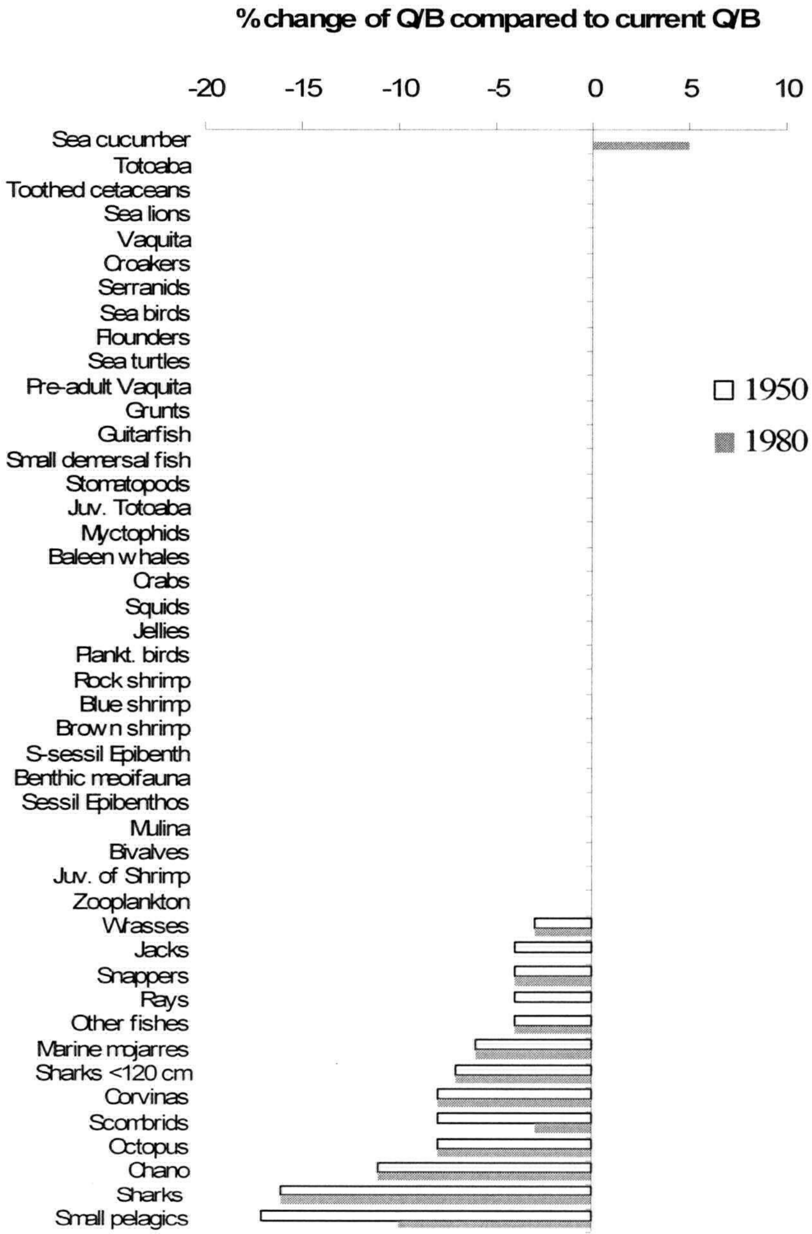

Figure 36. Change in Q/B of major groups in the upper Gulf of California from 1950 and (white bars) and 1980 (gray bars) compared to 2000.

3.3.3. Diet composition

The diet matrix from the 2000 UGC model described in Chapter II (Appendix 2) was used as a base for the trophic links and diets needed to built the 1950s and 1980s models (Appendix 3 and 4, respectively). This decision was taken based on the quality and quantity of diets reported in the upper Gulf after the mid 1980s (appendix 9 presents a summary of the sources of information employed), where the 2000 diets represented the best approach to rebuild the past trophic interactions in the region. It was assumed that predator preferences have changed very little in the past 50 years and that the changes in these interactions reflect the changes in abundances of the prey (i.e., increasing their vulnerabilities to predation during high abundances and vice versa). Table 8 shows changes in the diets estimated for sharks among the three models where the reduction of totoaba ingested is explained by the documented decline of the population of this species, or the increasing consumption of sea lions is a response to their increasing abundances (according to the LFK analysis). The 'Fishing down in the food web' trend observed in the upper Gulf is also assumed to have affected top predators such as sharks. This explains the increase in the preference for small fish such as corvinas and chanos in lower trophic levels instead of the large serranids and scombrids that were common in the region during 1950s (LFK analysis: in the opinion of local fishers). Appendices 3, 4 and 5 present the diet matrix of the 2000, 1980 and 1950 models, respectively.

Table 8. Estimated percentages of the prey ingested by large sharks in 2000, 1980s and 1950s in the upper Gulf of California. Last column on the right presents the percentage of changes in the preys consumed between 2000 and 1950.

Prey	2000	1980	1950	Change (%)
Totoaba	0.002	0.002	0.071	- 97 %
Small sharks	0.09	0.22	0.17	- 47 %
Serranids	0.027	0.03	0.039	-30 %
Scombrids	0.25	0.27	0.33	-24 %
Corvinas	0.08	0.07	0.082	-2 %
Vaquita	$1x10^{-5}$	$1x10^{-5}$	$1.1x10^{-5}$	<1%
Toothed cetaceans	0.014	0.015	0.012	+ 8%
Sea lions	0.09	0.08	0.06	+ 50%
Other fish	0.23	0.16	0.15	+ 53 %
Croakers	0.09	0.08	0.04	+ 120%
Chanos	0.12	0.07	0.04	+ 200 %

3.3.4. Catch data.

1980s model.

Several sources of information were used to assemble the 1980s catch. Most of the commercial landings were obtained from yearly INP reports. The final catch input in the 1980s model represents the average catch from 1978 to 1983. Shrimp, octopus, clam, sea cucumber and crab, landings were estimated from the official landings reported in San Felipe from 1977 to 1983, and provided by CRIP-Ensenada (Regional Fisheries Centre, Ensenada, Baja California), an office extension of the INP. The fishing fleet structure for this model was practically the same as for the 2000 model, but the artisanal traps and hookah diving fleets were not included because they were undeveloped in the early 1980s. Illegal and unreported catches were estimated for the major species exploited according to the analysis presented in Chapter II. Each input catch value used in the model represents the total extraction calculated for the group in the average year of 1980.

Discards from the industrial shrimp trawlers were considered to be of the same magnitude (10:1) and fish composition as those reported for the 2000 model. Vaquita was a special case since they were caught during the 1980s in all types of gillnets, including totoaba nets greater than 25 cm in mesh size (now prohibited by federal law), as well as legal nets for shrimps, chano, sierra, sharks and rays (ranging from 5 to 15 cm inches in mesh size; D'Agrosa *et al.*, 1995). Based on mortality estimates at El de Santa Clara, 13 vaquitas were killed annually in shrimp nets, 17 by the chano fishery, 7 in nets set for sharks and rays and 2 in nets for sierra and mackerel, for a total minimum annual mortality of 39 vaquitas during the early 1980s (D'Agrosa *et al.,* 1995). Vidal (1990) calculated that at least 110 vaquitas have been caught in totoaba and shark nets since the 1970s and he estimated that 23 vaquitas/year were killed during fishing activities.

1950s model.

Catch information for the 1950s model came from historical records of landings from CRIP-Ensenada, including records of shrimp and totoaba landings in the Port of San Felipe, Baja California. Information and time-series of landings (totoaba, sharks and shrimps) reported by Arvizu and Chávez (1970), Flanagan and Hendrickson (1976) and Magallón-Barajas (1987) were also considered and compared with those reported by CRIP-Ensenada. For a few species without official records of landings (sea turtles, corvinas, chanos and clams), the LFK (Local Fishers Knowledge) testimonies revealed that these species were exploited during the 1950s at a low intensity, and estimations of the catches were calculated using information from LFK interviews. According to the official records and LFK, the major species caught during the 1950s in the upper Gulf were totoaba and shrimps, followed by a few sharks and clams. According to LFK informants, local markets used to sell corvinas, flounders and sea turtles (LFK testimonies). For the 1950 model, only four types of gear were considered: offshore shrimp trawlers, artisanal shrimp gillnets, artisanal gillnets larger than 15 cm, and fishing rods. Unreported totoaba and shrimp catches estimated in Chapter II were added to the landings, and the final catch value was incorporated into the Ecopath model. The fish

composition of discards from trawls was considered the same as in 2000, but the ratio was lower. Fishers reported catching approximately 3-5 kg of 'trash' (low value fauna) with each kg of shrimp. So, for the 1950s model, the ratio of discards was set as 4:1 for the offshore fleet. This assumption was based on the opinions of local fishers that, during the last decade, it has been harder and harder to catch shrimp and each day more trawls are needed to reach the quota. They stated that "*today, just garbage* [low price fish] *is found*". Accordingly, the trash fish discards were considered lower in the 1950s than those estimated in the 2000 model.

No discards were included for the other three fleets. According to the LFK analysis, no vaquitas were caught accidentally in gillnets; however, a conservative value of 0.00019 t/km^2 (equivalent to 25 vaquitas caught per year or 0.5% of the 5,000 population estimated) was considered more realistic and was included in the analysis. Figure 37 summarizes the changes in the landings estimated from 1950 and 1980 in comparison to those reported in 2000.

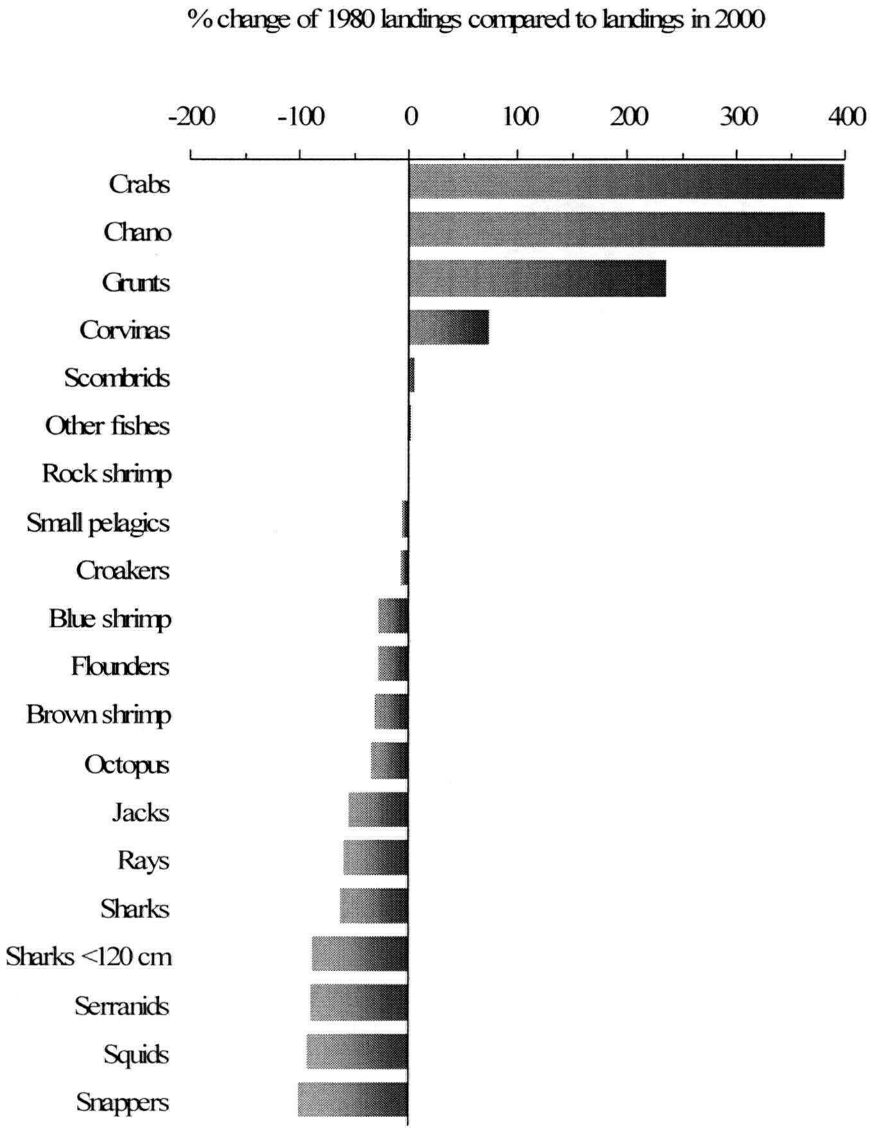

Figure 37. Change in landings of major groups in the upper Gulf of California from 1980 to 2000. Data provided by the Institute of National Fisheries (INP).

3.3.5. Biomass change.

1980s Model.

For the 1980s model, 70% of the 50 input biomass values were obtained from local surveys and published reports from direct biomass samplings in the upper Gulf using trawling surveys; 24% were calculated by Ecopath and just 6% of the biomasses were estimated using LFK modifications to the 2000 model values (sea lions, seabirds and sea turtles). Pérez-Mellado (1980) and Pérez-Mellado and Findley (1985) estimated the densities of sharks and rays based on a swept area method. In the case of fish groups, biomasses were calculated from surveys from 1978 to 1980 (Grande-Vidal, 1981), which reported abundances of jacks, corvinas, chano, serranids, scombrids, snappers, flounders, wrasses, grunts, and other fish. For invertebrate groups, a trawl sampling by Felix-Pico (1975) was employed to calculate the biomass of crabs, squids, jellies, blue and brown shrimps and rock shrimps (*Trachypenaeus similes pacificus*). Samples taken by Felix-Pico (1975) not only cover abundances of shrimp post-larvae (mainly blue shrimps), but also record standard lengths (5-40 mm). He reported an average abundance of 0.7995 post-larvae/m^2 (originally 7,995 PL/ha). This abundance was transformed into tonnes/km^2 using:

$$W = 0.008\ TL^3$$

Where,
W = weight (g)
TL = total length (cm)

Using a TL = 2.5 cm, the larvae have an average weight of 0.125 g and so an abundance of 0.7995 larvae/m^2 produces a biomass of 0.099 t/km^2.

In general, the biomasses estimated from the surveys by Félix-Pico (1975); Pérez-Mellado (1980) and Pérez-Mellado and Findley (1985) were based on the swept area method and their conversion to t/km^2 was done according to the equation proposed

by Gulland (1971):

$$\text{Biomass} = [K_3 \cdot C] / [T \cdot S_A \cdot V]$$

Where:

K_3 = conversion from minutes to hours

C = catch (kg)

T = trawling time (hours)

S_A = swept area (0.18 km^2/hr was estimated using a speed boat of 4 km/h and two nets of 12 m width).

V = vulnerability factor (default value = 0.5).

Another source of information employed to obtain past abundances was the number of mollusk shells (mainly bivalves) preserved in the southernmost portion of the Colorado River Delta in Baja California (Kowaleswski *et al.,* 2001; Flessa *et al.*, 2001; Rodriguez *et al.*, 2001). These deposits of bivalves or 'cheniers' (primarily the endemic species of *Mulina coloradensis*) are found as far as 80 km south of the mouth of the Colorado River, and they have supported an abundance of 3 to 5 clams per square meter since the 1980's (Kowaleswski *et al.* 2001 and Flessa *et al.*, 2001). The biomass value for these two groups was calculated assuming a density of 3 clams/m^2 with an average weight of 5g (without shells) distributed in a conservative area of 12 km^2 (west side of the delta), resulting in a biomass of 0.04 t/km^2 for clams and 0.004 t/km^2 for *M. coloradensis* (approximately 10% of the 1980-2000 mollusk composition of these cheniers was represented by this species; Kowaleswski *et al.,* 2001). In the case of the infaunal communities (polychaetes group), their biomass was estimated from core samples (with abundances reported in mg/m^2) taken during 1984, and published by Fernández-Alamo (1992).

Some information was available for marine mammals. Surveys by Villa (1986) reported 18 baleen whales in the upper Gulf (mainly Golfo de Santa Clara) during 1984. Using an average weight of 30 tonnes per whale over the 4,500 km^2 of area modeled resulted in a

biomass of 0.12 t/km^2 for this group. Two sporadic orcas (*Orcinus orca*) were observed in the Golfo de Santa Clara in 1988 (Delgado-Estrella *et al.*, 1994), and their biomass was incorporated into the toothed cetaceans. Dolphins biomass was assumed to be the same as that found in the 2000 model (based on the 1993 aerial surveys). Vaquita, its biomass was estimated using the 1986 survey that reported 506 vaquitas living in the upper Gulf (Vidal *et al.*, 1999). Using an average weight of 35 kg/vaquita, results in a biomass of 0.004 t/km^2. The biomasses of sea lions were estimated using LFK based on the abundances reported for the mid 1990s and were used for the 2000 model (Chapter II).

Stock assessment was used to establish the biomass of totoaba during the last five decades. An age-structured Virtual Population Analysis (VPA) used catch-at-length data from 1986 to 1991 (Figure 38, 1,280 totoaba analyzed) reported by Román-Rodriguez and Hammann (1997). The catch-at-length distribution was converted to catch-at-age (assuming a stable age distribution) according to the growth parameters of this species reported by Cisneros-Mata *et al.* (1995). This age distribution was then used to obtain past population sizes of totoaba retroactively from 1990 until 1950 through the VPA. The first step of this stock assessment was to calculate the annual natural mortality (M) using the model of Pauly (1984):

$$\text{Log } M = -0.0066 - 0.279 * \text{Log } L_{inf} + 0.6543 * \text{Log } K + 0.4634 \text{ Log } T$$

Where the growth parameters required for this model (K=0.152 and L_{inf} = 169.9 cm) were reported by Cisneros-Mata *et al.* (1995), and the average surface temperature of 20°C during spawning of totoaba (16-28 °C; Arvizu and Chávez 1970) resulted in a natural mortality of 0.27. The annual fishing mortality of Z = 0.414 for 1990 was reported by Cisneros-Mata *et al.* (1995) based on commercial catch-at-age, producing a fishing mortality of 0.141 that was used as terminal F for the VPA. Also, this figure presents the biomass estimated by the VPA, where a biomass of totoaba of 0.093 t/km^2 was calculated for 1980.

Zooplankton biomass was determined from 1974 oceanographic cruises (Farfán and Alvarez-Borrego 1992) that reported biomasses as high as 154 mg/m^3 (during August near the Colorado River mouth). An average of 12 mg/m^3 (dry weight) was used for the average year. This value was converted to t/km^2 using the ratio of 15:1 between dry weight and wet weight (according to Lavaniegos-Espejo and Lara-Lara, 1990). Assuming that the reported concentration is proportional to surface area, we get 0.012 $t/km^2/day$ or 4.38 $t/km^2/year$ times the conversion factor to wet weight, producing a biomass of 65.7 t/km^2 for the average year.

Phytoplankton biomass was incorporated into the model according to abundances in the range of 0.5-16 mg/m^3 for 1982 published by Valdéz-Holguín and Lara-Lara (1987). Similar abundances of phytoplankton in the upper Gulf were found in 1986 by Millán-Nuñez *et al.* (1999). Macrophyte biomass was calculated from a mean macrophyte net production of 47.9 mg C hr^{-1} m^{-2} in Puerto Peñasco (Littler and Littler, 1981).

In the absence of local data for sea lions, seabirds and turtles, their abundances were estimated using LFK from the 49 interviews conducted in the upper Gulf during 2002 (Chapter II presents a full description of this analysis). The abundance estimated for the 1980s by the fishers was based on the biomasses reported for these groups during the mid 1990s (Tables 5 and 6).

Finally, the detritus pool was recalculated from the formula presented by Pauly *et al.* (1993):

$$\text{Log } D = -2.41 + 0.954 \text{ Log } PP + 0.863 \text{ Log } E$$

Where,

D= detritus standing stock (gC/m^2)

PP = primary productivity ($gC/m^2/year$)

E = Euphotic depth (m)

Using the primary productivity of 2.76 ± 0.53 $gC/m^2/day$ reported by Valdez-Holguin *et*

al. (1985) and an average depth of 20m for the euphotic zone, the estimated detritus pool amounts to 65.9 t/km^2.

Figure 39 indicates proportional changes in the biomass estimates for the 50 model groups in the 1980s and 2000s models. It is worth noting that groups represented by small and highly dynamic organisms such as sardines, anchovies and squids exhibit the largest changes in biomass during the last 20 years; these changes are as high as 15-fold. These species are characterized by large population fluctuations (fossil records have shown that the populations of these small pelagics may change because of natural causes or fishing (Baumgartner *et al.* 1992; Lozano-Montes, 1997). It seems that these fluctuations in the biomass estimated in both models represent a red flag for the 1980 model, indicating that more accurate information is needed for these groups.

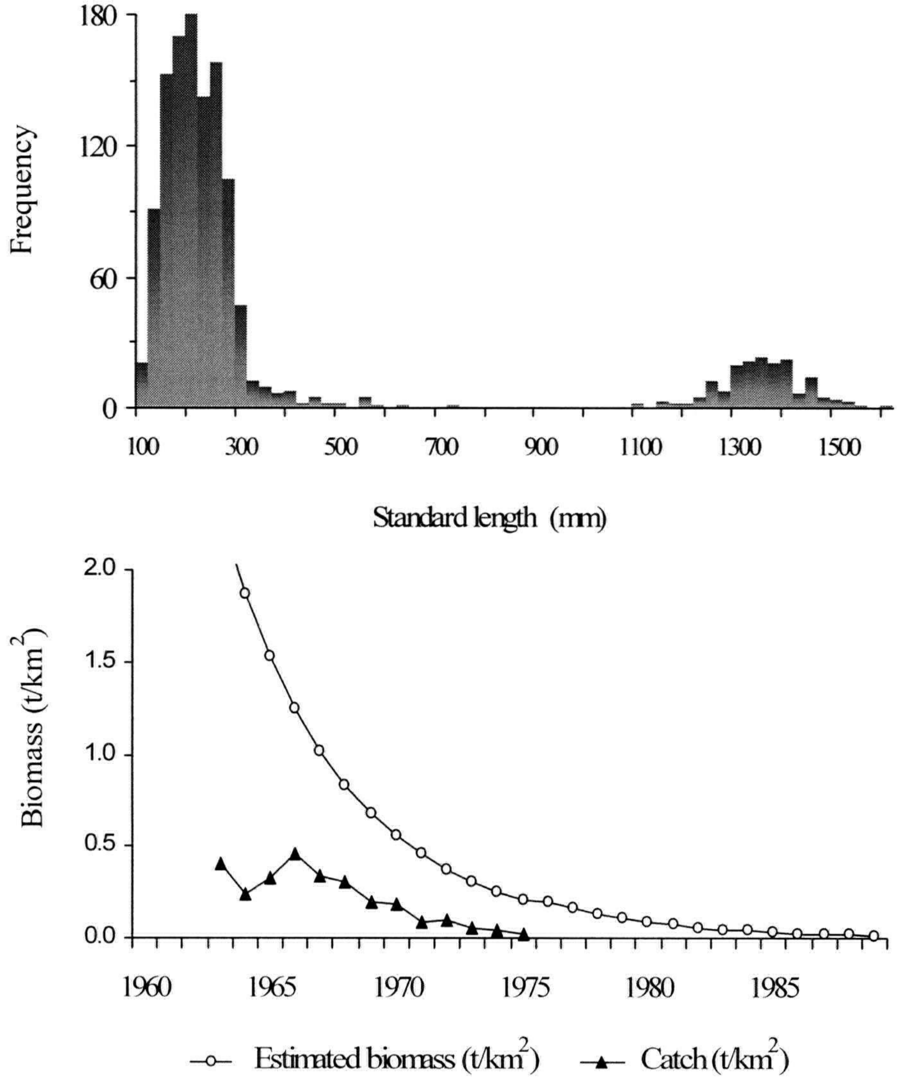

Figure 38. Upper panel presents the length-frequency distribution for 1,280 totoaba (25 mm intervals) collected from 1986 to 1991 in the upper Gulf of California by Román-Rodriguez and Hammann (1997). These data were used to estimate past biomasses using (age-structured) virtual population analysis (lower graph, white circles). For comparison, the reported catch is presented in dark triangles.

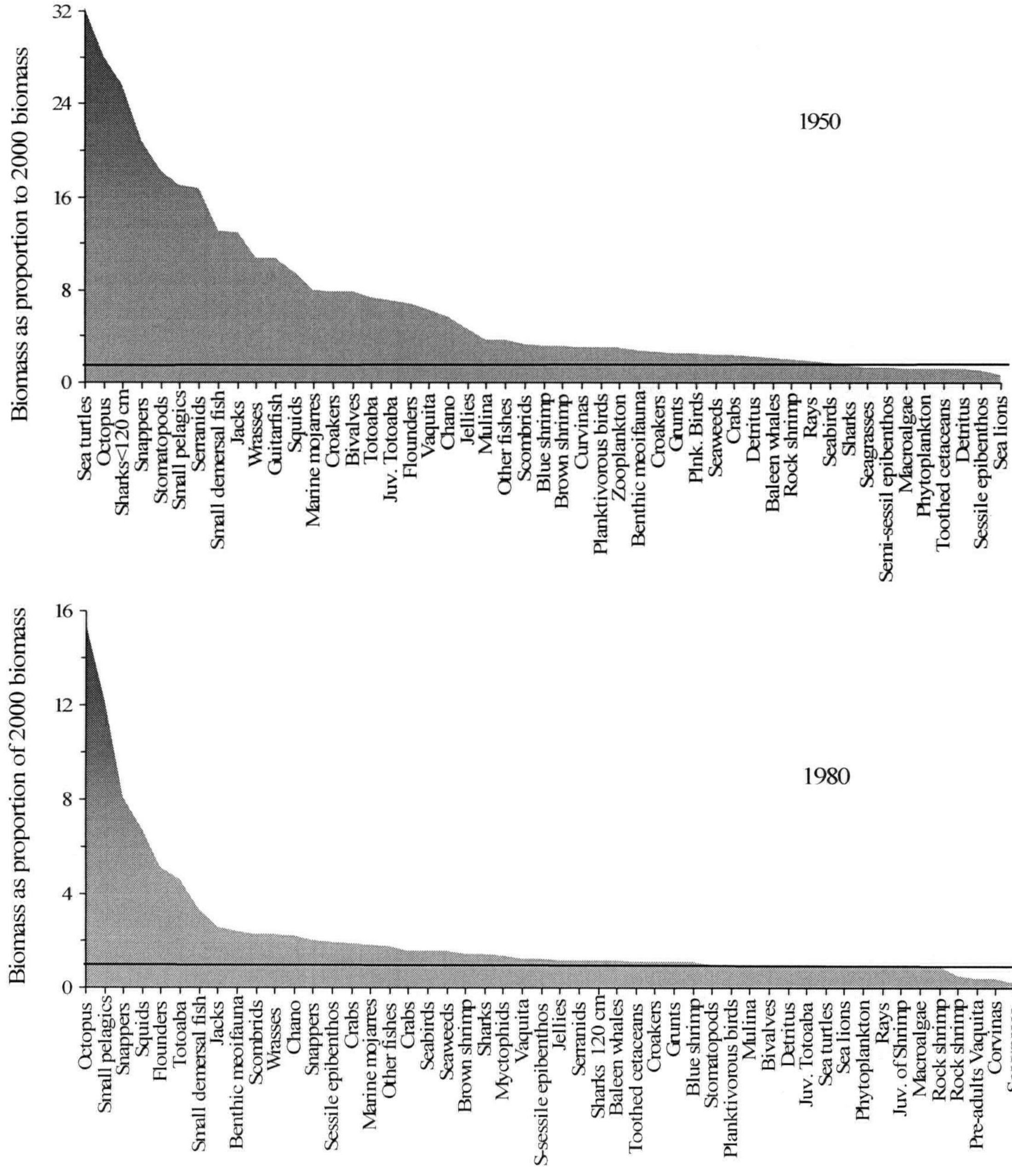

Figure 39. Changes in proportion of the biomass for the 50 groups in the upper Gulf of California from 1950 (upper panel) and 1980 (bottom graph) to present day. The horizontal line (value = 1.0) represents the current biomass.

1950s Model.

Building a 1950s model and running it forward to the 2000 model represents a unique opportunity to monitor how biomasses have changed throughout time in the upper Gulf as a result of natural causes, e.g., climate factors, human presence (dams and fishing) or some combination. This work represents a first attempt to go back in time to address critical question of what the upper Gulf of California was like *before* the 1960s when the completion of Glen Canyon Dam drastically depleted freshwater flows. However, since the earliest data for many model groups is from the 1980s, constructing a 1950s model represents a significant challenge. Despite the uncertainty and weakness of the 1950s model, it presents a framework to address questions of major ecological impact. Contributions from fisheries scientists, local fishers, historians and conservationists are welcome in order to improve this model.

The 1950s model exemplifies the potential role of interdisciplinary information in fisheries science and how qualitative data from other disciplines can be used to answer biological questions, explore past states of the ecosystem and try to quantify impacts previously thought to be inaccessible. Information from different sources such as local fisher knowledge (LFK), fossil records of clams (*Mulina coloradensis*), historic archives, oceanographic expeditions and published reports were important elements in modelling the upper Gulf as it was 50 years ago.

An intensive search during my 2003 field trip to the Northwest of Mexico, southern California and Arizona was conducted in order to obtain past abundances of the fauna in the upper Gulf. Several lists of fish records and field notes since 1947 were obtained. Major sources of information include the Fish Collection at the University of California at Los Angeles and the Marine Vertebrates Collection, Scripps Institution of Oceanography, University of California at San Diego, La Jolla, California. These records from the late 1940s and 50s, represent the first scientific expeditions to collect benthic organisms from the upper Gulf of California. They contain a complete list, description

and identification of the fish collected with bottom trawling nets; however, it was not possible to estimate absolute biomasses (t/km^2) for the list of species recorded for these two 1950 expeditions using swept area estimates because no specific information about the trawling time and speed of the vessels was given. The information contained in these collections was augmented by two other fish collections assembled during the 1970s and 1980s by the University of Arizona and Centro Ecológico de Sonora (Ecology Centre of Sonora). Trophic levels for each species in the sample list were taken from FishBase (Frose and Pauly, 2000). The analysis shows a reduction in the mean trophic level of fish since the 1950s (Fig. 40), and the trend obtained is in agreement with the results found by Sala *et al.* (2004). Observed changes may have resulted from intense fishing by shrimp trawlers that were in the region for more than 60 years, supporting the 'fishing down in the food web' concept described by Pauly *et al.* (1998a).

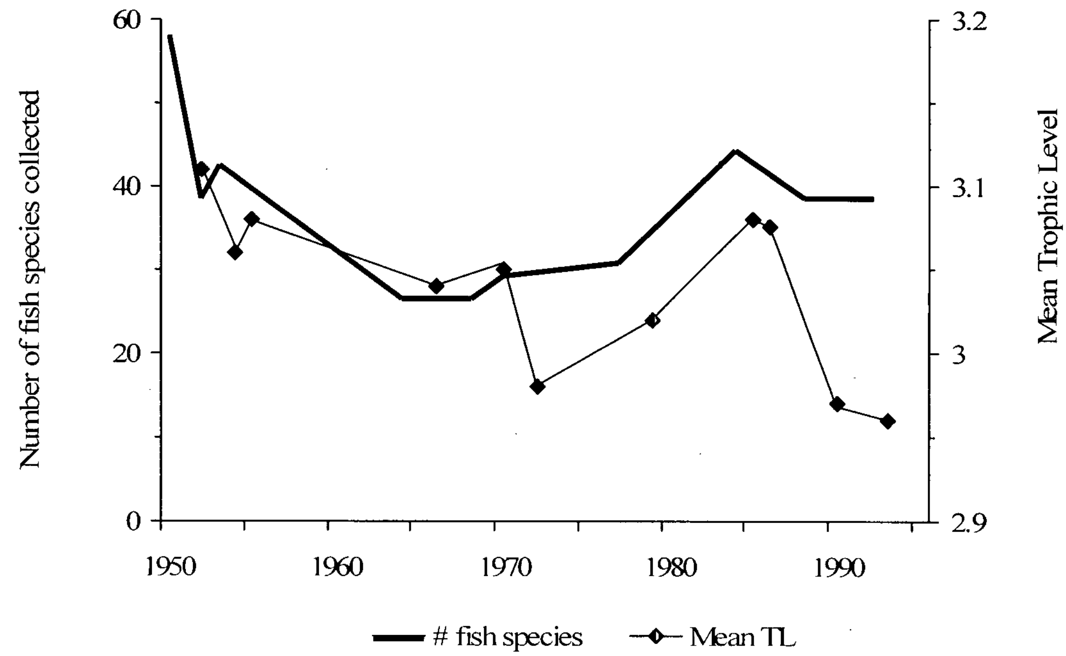

Figure 40. Mean trophic level of the benthic fish collected during nineteen trawl surveys conducted in the upper Gulf of California since 1952. The trend indicates a reduction of the mean trophic level of benthic fauna, possibly associated with intense shrimp trawling for more than 60 years.

From 1967 to 1969, the Fishery Agency (now named Institute of National Fisheries, INP) conducted a series of bottom trawling surveys in the upper Gulf of California to establish the composition and abundance shrimp fishery bycatch. These trawl samples represent the earliest biomass estimates of local benthos. The biomasses of biomasses of totoaba, corvinas, groupers, cabrillas (*Ephinephelus* spp), sierras (*Scomberomorus* spp), chanos, flounders, 'other fishes' (*Balistes* spp, *Pomadasys* spp, *Mugil* spp, *Pomacanthus* spp and more), crabs, squids, octopus reported by Chavez and Arvízu in 1970 (Table 9) were to cross-validate the 1950 relative biomass estimation obtained from LFK interviews. The relative biomass estimated by LFK was converted to absolute values (t/km^2) and incorporated into the 1950s model. The absolute biomass estimates of these groups after the balancing process are presented in Table 12.

Table 9. 1968 biomasses from upper Gulf of California surveys (Chávez and Arvízu, 1970). These absolute abundances (t/km^2) were employed to estimate relative biomass for specific groups based on the factor of conversion that represents the average change of abundance perceived from 1950 to 1970 by the 49 fishers of the upper Gulf of California interviewed during 2003.

Group	Absolute biomass from 1968-1969 surveys (Chávez and Arvizu, 1970). (t/km^2)	Factor of conversion from absolute biomass to relative biomass 1970 and 1950. (times)	Relative biomass from LFK for 1950 model based on 1968-1969 surveys. (t/km^2)
Blue Shrimps	0.23	8x	1.86
Corvinas	0.80	15x	12.03
Flounders	0.25	9x	2.26
Chanos	0.61	15x	9.27
Crabs	0.29	9x	2.68
Squids	0.14	11x	1.59

Zooplankton biomass was estimated from samples collected in 1956 and 1957 by the CalCOFI expeditions run by Scripps Institution of Oceanography (La, Jolla, California) in the Gulf of California, including seven stations in the northernmost region of the Gulf. Zooplankton abundance -reported by these expeditions was based on a displacement

volume method ($ml/1000m^3$). The conversion of volume displaced to dry weight (mg/m^3) used was suggested by Lavaniegos and Lara-Lara (1983) (Lavaniegos-Espejo and Lara-Lara, 1990; Lavaniegos-Espejo personal communication). Table 10 shows the abundances of zooplankton collected in 1957, their conversion to dry weight and finally to biomass. An average biomass of 78.1 t/ km^2 was estimated and incorporated into the 1950s model.

Figure 36 presents a comparison of the zooplankton abundances estimated in the 1950's, 1980s and 2000s models, and shows an apparent trend of reduction in the zooplankton abundances. At the moment, there is no conclusive evidence that this decline of zooplankton in the upper Gulf is a real trend in the GoC or that it represents an overestimation of the biomass calculated in the 1950s (with a considerable SD = 34 t/km^2). However, between 1950 to1970 and the early 1990s zooplankton levels dropped by 80% in the southern portion of the California current (off southern California) as sea surface temperatures increased, resulting in a reduction of upwelling and food supply for zooplankton (Roemmich, and McGowan. 1995). More research in the upper GoC is needed to confirm the possible decline of zooplankton and the role of climate and river inflow during the last 60 years.

Table 10. Relative abundance of zooplankton ($cm^3/1000m^3$) collected by Scripps in the CalCOFI expeditions to the Gulf of California in 1956-57. Conversion to absolute values (t/km^2) according to Lavaniegos and Lara-Lara (1983).

Expedition	Dry weight mg/m^3	Wet Weight mg/m^3	Biomass t/km^2
April 1956	60.6	184.9	67.5
April 1957	121.2	369.6	134.9
June 1957	60.6	184.9	67.5
Aug 1957	37.9	115.6	42.2
Average	70.1 ± 34.2	213.8 ± 94.3	78.1 ± 34.4

The waters of the Gulf of California were described as "fabulously rich" by expeditions conducted in 1939 and 1940 on the research vessel 'E.W. Scripps' by Scripps Institution of Oceanography, SIO (SIO, 1969). These two expeditions represented the first systematic sampling of the entire Gulf, and for the first time, phytoplankton was collected from the surface down to 60 m at intervals of 10 m (Gilbert and Allen, 1943). An average superficial value of primary productivity 12 $mgC/m^3/day$ (within the range 0.5 to 24.4 $mgC/m^3/day$ reported in 1940) was used to estimate the biomass of phytoplankton for the 1950s model. This average production was converted to an integrated primary production ($gC/m^2/day$) using the factor of 57.68 reported for the shallow waters of the upper Gulf by Zeitzchel (1969), resulting in 0.201 $C/m^2/day$ that is equivalent to 73.13 t/km^2 for the average year, value employed for the Ecopath model. A similar primary productivity of 0.27 $gC/m^2/day$ (biomass = 98.55 t/km^2) was obtained in 1960 in the Central GoC region (Angel de la Guarda Island) by SIO (Scripps Institution of Oceanography, cruise TO-60-1). Primary productivity reported by Millán *et al.* (1999) and abundances of zooplankton obtained by Farfán and Alvarez-Borrego (1992) were incorporated into the 2000 model (Fig. 36).

The biomasses of non-exploited groups such as baleen whales, dolphins, sea lions, seabirds and turtles were estimated using the relative abundances from the LFK analysis (Chapter II). These were used to modify the 1990's absolute biomasses estimated by surveys and other sources of information (Appendix 10 and 11). Vaquita biomass for the 1950s period was calculated using the average carrying capacity for this species estimated by Ortiz (2002) i.e., 5,000 vaquitas (Fig. 41), resulting in a biomass of 0.038 t/km^2.

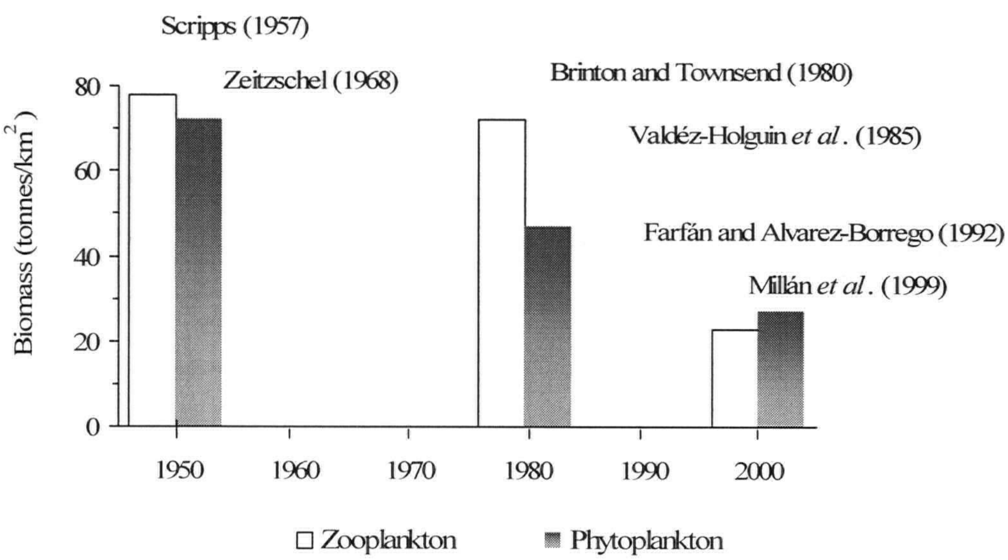

Figure 41. Absolute biomass of zooplankton and phytoplankton estimated for the 1950s (based on Scripps cruises in 1957 and Zeitzchel, 1968), 1980s (Brinton and Townsend, 1980; Valdéz-Holguin *et al.*, 1985) and 2000 models from Farfán and Alvarez-Borrego (1992), and Millán *et al.* (1999). There is no confirmation of the apparent decline of zooplankton in the upper Gulf of California, but a similar trend has been reported in the southern California Current in the last 60 years as a response to increasing sea surface temperatures (Roemmich and McGowan, 1995).

3.4. Balancing the 1980 and 1950 Ecopath models.

In the draft 1980 Ecopath model, seventeen out of 50 groups were unbalanced with an average EE of 6.7 ± 7.8, where 11 were fish groups, 5 invertebrates and 2 marine mammals. The higher values of EE were associated with invertebrates and benthic fish. For the 1950 model, the number of unbalanced groups was higher than that in the 1980 model. A total of 27 groups were out of balance with EE as high as 41.8 (average EE = 14.3 ± 12.5), reflecting the higher uncertainty in this model. Both models were balanced manually with adjustments to diet matrices, reducing both cannibalism (liberating this energy to other groups) and predatory consumption (shifting the consumption pressure to other prey with lower EE). For example, the biomasses of the groups consumed by sharks in the 1950 model (sierras, hakes, totoaba, sea lions, corvinas) were increased (by less than 20%) in order to meet the high predation mortality imposed by the abundant population of sharks (biomass = 4.1 t/km^2). Final adjustments in the balancing process reduced consumption rates, Q/B, between 5% and 15% for some of the benthic groups (i.e., crabs, octopus, sea cucumber, semi-sessile and sessile epibenthos). The final balanced parameter values for the 1980 and 1950 models are shown in Tables 13 and 14.

3.4.1. Uncertainty in the 1980s and 1950s models.

Unbalanced groups in the 1950 and 1980 models drew attention to the areas and groups in the upper Gulf of California that are not very well understood, raising a red flag for more intense research in the benthic communities (fish and invertebrates). A more robust biology of these groups could help reduce uncertainty about the role of benthic fauna in the upper Gulf, including their groups' interactions with humans. The trophic imbalances of these groups should be resolved in future models by improving understanding of their biology rather than by solving the linear equations of the model.

Once both models were balanced, their consistencies were evaluated through the respiration to biomass ratio (R/B). The general trend in these models was for R/B was to increase at higher trophic levels, as expected, where more active species are found.

Another element included in the Ecopath software that assists is the sensitivity analysis in the *pedigree* routine. The pedigree index (P) categorizes the origin of the sources of information used to build the model, measuring the uncertainty associated according to the type of data for each of the five basic parameters of the model (Biomass, P/B, Q/B, diet composition and catches). The P index ranges from 0 for data with no local input to 1 for local data. This P index can be used as a measure of fit for Ecopath models. Analysis of 211 categories across the 50 groups in the 1980s model gave a value of 0.59. In the 1950s model, the pedigree routine reflects the higher uncertainty of the model with a P = 0.47, mainly explained by the indirect method of LFK employed to estimate the biomass of more than 20 groups. Figure 42 shows the P index calculated among the 1950, 1980 and 2000 models.

The predicted biomasses from the past models are compared with those estimated from stock assessment or surveys in Chapter IV in order to evaluate discrepancies and improve their accuracy. Chapter IV also links the two past models with the 2000 model in a first attempt to quantify changes in biomasses and dynamics of the species living in the upper Gulf after 50 years of water diversion.

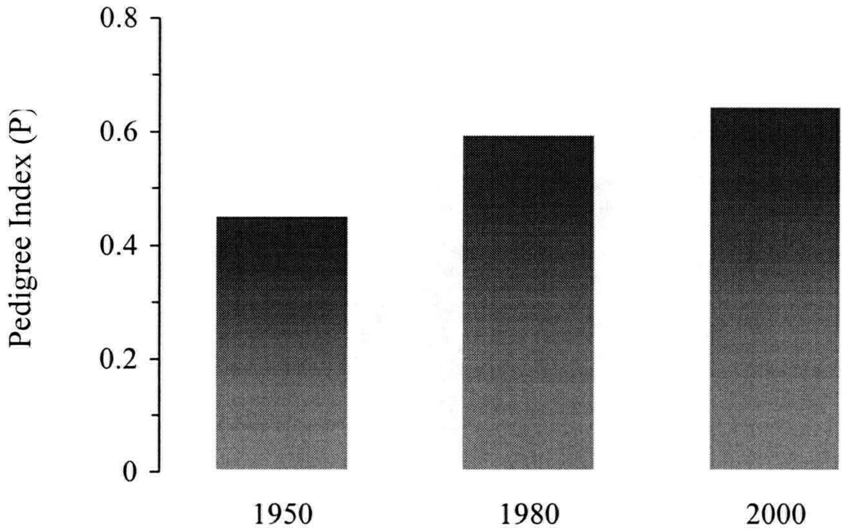

Figure 42. Pedigree indices for the 1950, 1980 and 2000 models built in the upper Gulf of California. This index categorizes the origin of the sources data for the models. It ranges from 0 for data with no local input to 1 for local data.

Table 11. Basic parameters for the 1980s upper Gulf of California model. Values in bold have been calculated using Ecopath. The sources of information used to build this model are presented in appendix 10.

Group name	TL	Habitat %	B (t/km^2)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	EE
Sharks	**4.32**	0.75	2.215	0.86	2.5	**0.99**
Sharks < 120 cm	**3.61**	1	3.405	0.78	3.0	**0.99**
Totoaba	**3.63**	0.9	0.073	0.37	4.8	**0.64**
Toothed cetaceans	**3.87**	0.95	0.250	0.20	27.0	**0.78**
Sea lions	**3.74**	1	0.27	0.40	16	**0.75**
Vaquita	**3.84**	0.8	0.004	0.60	18.0	**0.00**
Grunts	**2.03**	1	**1.789**	0.67	3.9	0.95
Carangids	**3.48**	0.95	1.045	0.65	3.2	**1.00**
Corvinas	**2.29**	1	1.931	0.58	7.2	**0.95**
Lutjanids	**3.01**	1	1.46	0.32	3.2	**0.96**
Scombrids	**4.16**	1	3.871	0.66	3.4	**0.93**
Groupers	**3.39**	1	0.391	2.87	5.3	**0.73**
Seabirds	**4.16**	0.3	0.002	5.40	40.0	**0.52**
Rays	**2.4**	1	2.12	0.64	7.2	**0.54**
Flounders	**2.19**	1	1.681	1.35	4.8	**0.92**
Wrasses	**3.41**	0.7	**0.969**	0.48	7.6	0.95
Chanos	**2.91**	1	**3.596**	0.72	8.6	0.95
Sea turtles	**2.65**	0.2	0.003	0.21	4.0	**0.22**
Pre-adult Vaquita	**3.92**	0.9	**4.68E-07**	**8.00**	40.0	0.95
Sciaenids	**2.78**	0.9	**0.877**	1.37	16.5	**0.96**
Gerreidae	**2.15**	0.85	3.128	1.20	6.6	**0.87**
Guitarfish	**2.55**	0.7	**2.820**	0.47	3.3	0.95
Small demersal fish	**2.15**	1	**8.004**	0.85	7.5	0.95
Other fishes	**2.39**	1	12.234	0.99	6.2	**1.00**
Octopus	**2.82**	0.9	**1.241**	3.94	8.8	0.95
Stomatopods	**3.03**	1	0.882	4.40	15.5	**0.96**
Juv. Totoaba	**3.06**	1	0.002	**2.80**	14.0	**0.17**
Myctophids	**3.18**	0.7	**2.599**	2.28	7.2	0.95
Baleen whales	**3.24**	0.2	0.12	0.05	11.0	**0.79**
Crabs	**2.18**	1	1.83	2.87	10.7	**0.97**
Squid	**3.49**	1	1.14	5.64	22.5	**0.96**
Small pelagics	**3.24**	0.9	2.673	2.59	10.3	**0.99**
Jellies	**3.25**	0.8	0.448	25.00	40.0	**0.52**
Plankt. birds	**2.4**	0.02	0.00002	**9.00**	45.0	**0.00**
Rock shrimp	**2.57**	0.7	0.205	4.95	28.7	**0.78**
Blue shrimp	**2.53**	1	0.63	5.98	28.7	**0.62**
Brown shrimp	**2.58**	0.9	0.153	4.00	28.7	**0.72**
Semi-sessile epibenthos	**2.38**	0.7	**1.639**	2.20	8.5	0.95
Sea cucumber	**2**	0.95	**0.0358**	4.10	5.6	0.95
Benthic meoifauna	**2.1**	1	**16.646**	6.70	25.0	0.95
Sessile epibenthos	**2.34**	0.85	**4.533**	2.70	15.0	0.95

Table 11. Continuation

Group name	TL	Habitat %	B (t/km^2)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	EE
M. coloradensis	**2.16**	0.095	0.005	1.14	23.0	**0.99**
Bivalves	**2.15**	0.055	0.048	1.15	25.0	**0.92**
Juv. of Shrimp	**2.41**	0.5	0.099	**12.00**	60.0	0.61
Zooplankton	**2.25**	1	65.71	18.00	60.0	**0.85**
Seagrasses	**1**	0.1	**0.17**	15.00	-	0.95
Seaweeds	**1**	0.2	**0.38**	15.24	-	0.95
Phytoplankton	**1**	1	44.79	60.00	-	**0.92**
Macroalgae	**1**	0.7	1.232	60.00	-	**0.65**
Detritus	**1**	1	28.751	-	-	**0.28**

Table 12. Basic parameters for the 1950s upper Gulf of California model. Values in bold have been calculated using Ecopath. The sources of information used to build this model are presented in appendix 11.

Group name	TL	Habitat %	B ($t\ km^{-2}$)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	EE
Sharks	**4.12**	0.6	4.134	0.48	2.5	**0.76**
Toothed cetaceans	**3.95**	0.9	0.279	0.2	27	**0.85**
Totoaba	**3.89**	1	2.146	0.56	4.8	**0.93**
Scombrids	**3.72**	1	5.67	0.58	3.1	**0.94**
Sea lions	**3.69**	0.95	0.185	0.4	16	**0.97**
Seabirds	**3.57**	0.35	0.002	5.4	40	**0.93**
Vaquita	**3.53**	1	0.038	0.6	18	**0.17**
Sharks <120 cm	**3.46**	0.95	4.227	0.48	3	**0.91**
Sciaenids	**3.32**	1	1.594	5.64	22.5	**0.96**
Pre-adult Vaquita	**3.3**	1	**0.000107**	**8**	40	0.95
Groupers	**3.18**	1	**4.102**	0.87	5.2	0.95
Carangids	**3.17**	0.9	**5.038**	0.55	3.2	0.95
Baleen whales	**3.17**	0.3	0.441	0.05	11	**0**
Myctophids	**2.97**	0.55	**4.049**	2.28	7.2	0.95
Small pelagics	**2.96**	1	3.587	2.29	8.3	**0.88**
Juv. Totoaba	**2.84**	1	0.014	**2.8**	14	**0.46**
Lutjanids	**2.8**	1	**13.323**	0.48	3.2	0.95
Wrasses	**2.77**	0.7	**4.668**	0.36	7.6	0.95
Croakers	**2.65**	1	**12.764**	0.51	3.9	0.95
Guitarfish	**2.54**	0.7	**3.324**	0.41	3.3	0.95
Stomatopods	**2.54**	1	**16.174**	4.4	15.5	0.95
Octopus	**2.51**	0.9	**2.254**	3.5	8.8	0.95
Flaounders	**2.47**	1	2.261	0.78	4.8	**0.7**
Rays	**2.35**	1	4.31	0.41	7	**0.86**
Sea turtles	**2.35**	0.8	0.097	0.27	4	**0.4**
Grunts	**2.34**	0.9	**6.019**	0.98	16.5	0.95

Table 12. Continuation.

Group name	TL	Habitat %	B (t km^{-2})	P/B (year^{-1})	Q/B (year^{-1})	EE
Chanos	**2.33**	1	9.2017	0.61	8.6	**0.98**
Other fishes	**2.28**	1	**25.8175**	0.91	6.2	0.95
Corvinas	**2.26**	1	12	0.72	7.2	**0.98**
Brown shrimp	**2.19**	1	0.247	4.4	28.7	**0.12**
Rock shrimp	**2.17**	1	0.3202	4.95	28.7	**0.31**
Gerreidae	**2.17**	0.95	**13.964**	1.13	6.6	0.95
Small demersal fish	**2.16**	1	**34.578**	0.94	7.5	0.95
Plankt. Birds	**2.15**	0.04	0.0000605	**9**	45	**0**
Blue shrimp	**2.15**	1	1.86	5.98	28.7	**0.26**
Zooplankton	**2.14**	1	78.114	18	60	**0.61**
M. coloradensis	**2.15**	0.15	0.0186	1.14	23	**0.01**
Bivalves	**2.15**	0.15	0.4298	1.15	25	**0.25**
Sessile Epibenthos	**2.14**	0.85	**2.6065**	2.7	15	0.95
Semi-sessile epibenthos	**2.05**	0.9	**1.7156**	2.2	8.2	0.95
Crabs	**2.02**	1	2.6802	2.87	10.7	**0.84**
Juv. of Shrimp	**2.02**	0.6	**0.053**	**12**	60	0.95
Sea cucumber	**2**	0.95	**0.0659**	4.1	5.6	**0.43**
Benthic meoifauna	**2**	1	**18.6195**	6.7	25	0.95
Phytoplankton	**1**	1	73.167	60	-	**0.94**
Macroalgae	**1**	0.7	**1.3626**	60	-	0.95
Seagrasses	**1**	0.15	**0.3333**	15	-	0.95
Seaweeds	**1**	0.25	**0.5128**	15.24	-	0.95
Detritus	**1**	1	65.89	-	-	**0.46**

Chapter IV.

Connecting the past with the present: tuning the 1950, 1980 and 2000 models.

4.1. Connection and fitting between the 1950, 1980 and 2000 models.

An Ecopath model represents a description of an ecosystem at one particular time and it gives no evaluation of possible changes in biomass associated with differences in fishing mortalities through a period of time. Responses of the biomass pools to fishing mortality and other factors in the system may be tested using the dynamic simulator *Ecosim*. These dynamic simulations may be run alongside biomasses estimated from direct surveys or stock assessment data to adjust the ecosystem model to reflect changes that have been observed and documented. This process is known as 'tuning' (Christensen *et al.*, 2004). The basic procedure and details for the tuning of the Ecopath ecosystem models were explained in Section 4 of Chapter II.

4.1.1. Points to be considered in the reconstruction of the past.

One problem had to be overcome before connecting these models and simulating dynamics of the upper Gulf from the 1950s to the present. There is no reliable diet information or bycatch estimates from the 1950s. Both Ecopath and Ecosim simulations are highly sensitive to the initial diet matrices, since these determine the base predation mortality rates and the rates of effective search for prey by predators. This issue was addressed by using the 2000 Ecopath model as an initial state including its diet matrix (with the best scientific information available) and bycatch proportions as first guesses for the 1950s model. The main benefit of this approach is that (unknown) diet composition and biomasses for the 1950s model remain consistent with those implied by the 2000 model.

The criteria of how well the above scheme worked was to compare the time-series of biomass from 1950 to 2000 predicted by Ecosim with those obtained from direct surveys

in the upper Gulf. A second approach, which involved the connection of the past and present models, was to adjust the 'feeding time' parameter in Ecosim that determines how a given group adjusts its time spent on feeding (implying vulnerability to predation) in response to changes in prey availability. Low parameter values (0.2) did not change the overall biomasses predicted by Ecosim for the three species used in the tuning.

4.1.2. Tuning the 1950s and 1980s upper Gulf of California Ecosystem Models.

To tune the 1950s and 1980s models, it was necessary to generate annual fishing mortalities for the two main species, totoaba and shrimps, that have been exploited commercially since the 1950s. This process involved calculating the fishing mortality rate imposed by trawling and gillnet fleets on these three groups in the Ecopath base year as $F_{ji0} = Y_{ji0}/B_{i0}$, where Y_{ji0} is mean catch (1950-2000) of group i by fleet j, and B_{i0} is the mean biomass during the year (estimated by direct surveys in the area or by stock assessment). The mean yearly catch was then added to the IUU (illegal, unreported and unregulated fishing) estimations for these three species presented in chapter II. Sharks were not considered in the tuning of past models due to the lack of reliable biological and fishing information for this group.

The landings recorded in the upper Gulf (mainly San Felipe Port) for the species involved in the tuning process were provided by CRIP-Ensenada, an office extension of the INP. Information and time-series of landings (totoaba and shrimps) reported by Arvizu and Chávez (1970), Flanagan and Hendrickson (1976) and Magallón-Barajas (1987) were also considered and compared with those reported by CRIP-Ensenada. In the absence of biomass estimation, fishing mortality was held at the previous year's level (or to the earliest previous value).

For totoaba, a continuous time-series of annual fishing mortality from 1950 to 2000 (read as a CSV file) was estimated from biomasses calculated from VPA (details of this stock

assessment are explained in Chapter II, section 4) and from the historical records of landings reported by CRIP-Ensenada from 1940 until 1978, when this fishery was closed. After 1978, fishing mortality of this species was assumed to remain constant at the 1977 value (F=0.11). Figure 43 presents the annual fishing mortality, catch and biomass of totoaba used in the tuning process.

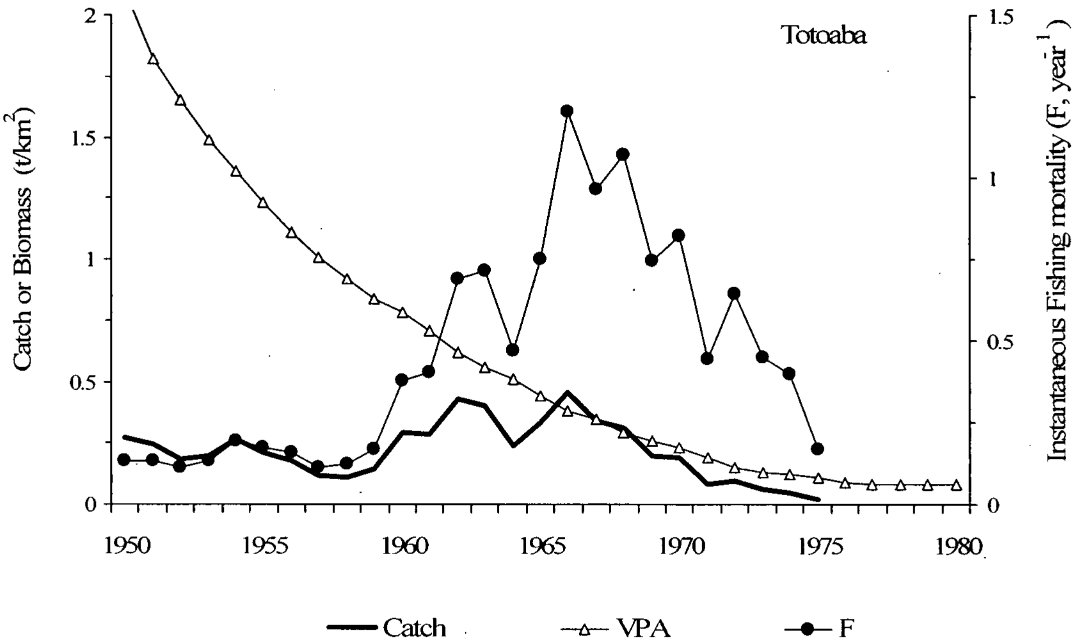

Figure 43. Annual fishing mortality from 1950 to 1978 (black circles) of the Gulf giant croaker or totoaba (*Totoaba macdonaldi*) in the UGC using stock assessment to estimate past biomasses from catches (solid line) reported by the CRIP-Ensenada (VPA biomass; white triangles) until 1978 when this fishery collapsed and was banned. The time-series of fishing mortality of totoaba was one of those employed to tune and connect the past and present UGC models.

In the case of blue shrimps from 1950-1965 it was necessary to use the LFK to estimate past abundance because there are no surveys or other sources of local abundance information before 1965. These LFK estimates were combined with formal scientific biomass surveys in the area from the end of the 1960s until 1995 (Félix-Pico, 1975; Pérez-Mellado, 1980; Pérez-Mellado and Findley, 1985; CRIP-Ensenada, 1995). Figure

44 represents an example of how LFK estimates (black circles) were included in the estimation of past biomasses (1950-1960). LFK was a key element in producing the time-series of annual fishing mortalities from 1950-2000 required to tune the three models of the UGC.

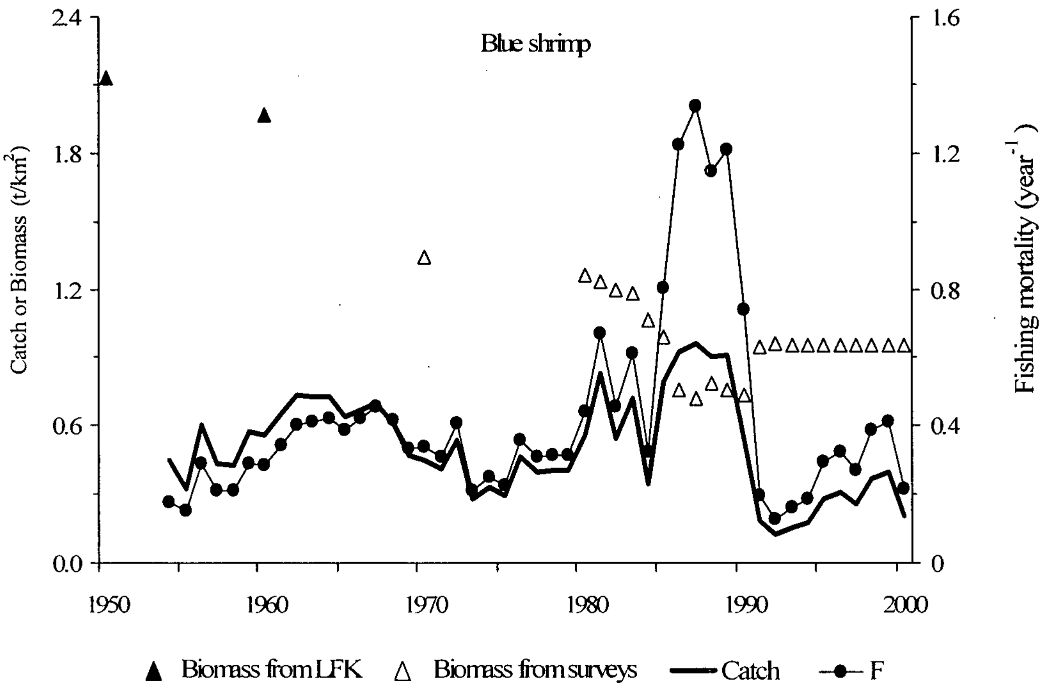

Figure 44. Estimation of annual fishing mortality (circles) of blue shrimp (*L. stylirostris*) in the upper Gulf of California from 1954 to 2000 using catch data reported by the INP (line), and local biomass surveys (white triangles) conducted by Felix-Pico, 1975; Pérez-Mellado, 1980; Pérez-Mellado and Findley, 1985; and CRIP-Ensenada, 1995. Perception of the average abundances from 1950 to 1960 (black triangles) estimated from interviews with local fishers (see Chapter III). The annual fishing mortality was used to drive the fitting and connection of the 1950s, 1980s and 2000 UGC models.

During this tuning process (through the fitting of the trophic models using a time series of biomass, catch and fishing mortality), each *Ecosim* run generated a statistical measure of the goodness of fit of the time series data employed was generated each time Ecosim was run. This goodness of fit is represented by a weighted sum of squared deviations (SS) of log biomasses from log predicted biomasses. Using this criterion, it was possible to

search for vulnerabilities that gave the best 'fits' of Ecosim to the time series of biomass and catch, and then selecting the best overall model with the lowest SS. Figure 45 shows the best model fitted (SS=27.42) comparing the biomass and catches observed from 1950 until 2000 of totoaba and blue shrimps with those estimated by the model fitted through the 50-year time-series of fishing mortalities estimated for both species.

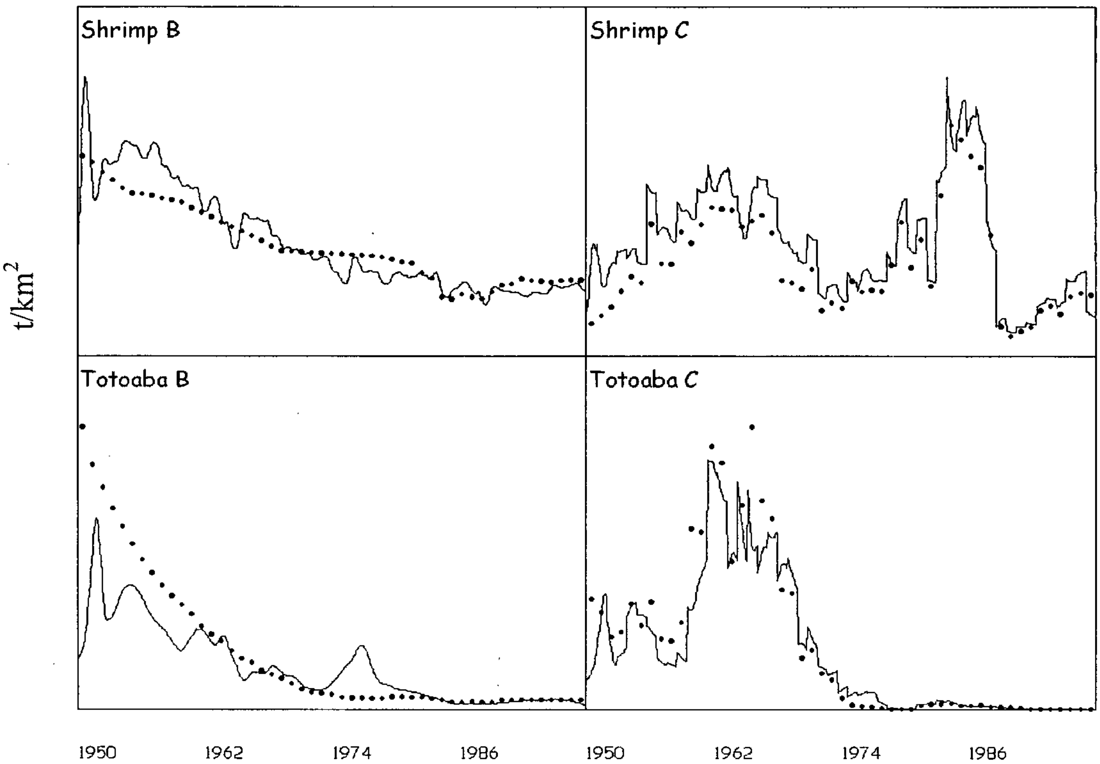

Figure 45. Fits to time series (screen capture) for the biomass and catch of shrimps and totoaba, the two principal species exploited in the upper Gulf of California since the 1950s. Dots indicate time series data since 1950 from assessments. Lines show Ecosim simulation results for the fitting of biomasses (B) and catches (C). Residual sum of squares (SS) has a value of 27.42. This value was compared with that obtained from the tuning after environmental factors were included. Vertical axis is expressed in t/km^2.

4.1.3. Improving the fitted model: Climate influence.

The interaction between the ocean and the atmosphere is a key element to be considered in the modelling of marine ecosystems. Changing environments can change ecosystems and these changes can be manifested by a shift in productivity, abundance and distribution of many species (Polovina *et al.*, 1994; Francis and Hare 1994, Hayward, 1997; Pitcher *et al.,* 2005). In order to try to capture the complex interactions between biology and physics in the upper Gulf, an environmental process was included into the fitted model. The climate influence incorporated in the tuning was represented by a time-series from 1950-2000 of the Colorado River discharge below the Hoover Dam (Fig. 2). This environmental forcing function includes the changes in the river flow associated with strong precipitation years during El Niño events such as 1957, 1983, 1993 and 1997 (Lavín, 1999 and Lavín *et al.*, 2003): Changes in water and sediments delivered by the Colorado River from 1950-2000 affected only primary production.

Including the environmental factor resulted in an improvement in fit, the overall SS=22.61 was 18% lower than without considering climate factors (SS= 27.42; Figure 46). This improved model including the climate series was used for the dynamic simulations and quantification of the water diversion impact in the upper Gulf of California.

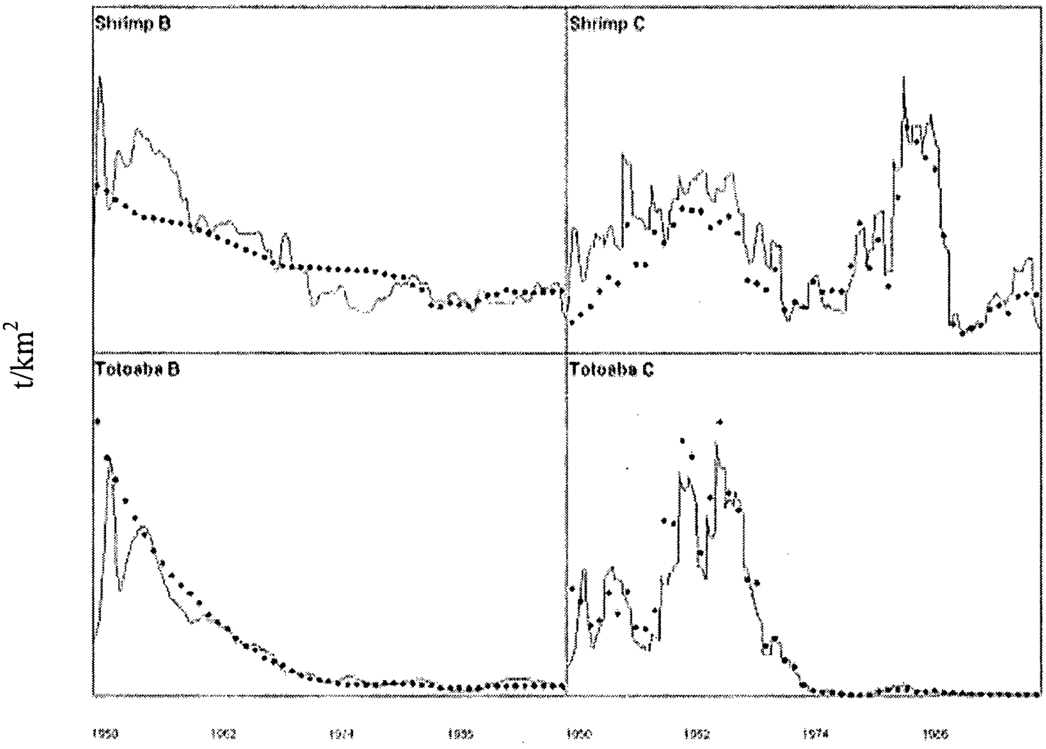

Figure 46. Improved fit of the upper Gulf of California Ecosim model (screen capture) including the Colorado River discharge from 1950-2000 as a forcing function affecting primary productivity. Taking environmental influence into account improved the model, resulting in an overall SS=22.61 compared with a SS=27.42 obtained without the climate factor (Figure 45).

4.1.4. Vulnerabilities resulting from the tuning.

In Ecosim, vulnerabilities (V) are assigned to individual predator/prey relationships, indicating whether the biomass of different groups is controlled primarily by predator or by prey. In Ecosim, vulnerabilities range from 1 to ∞; when V takes high values ('top down'), a high proportion of the biomass is vulnerable to predation. If V is closer to 1.0 ('bottom up'), then prey have the opportunity to find refuge from predators. In the three UGC models, Vs were based both on tuning to biomass data and on the trophic level of the prey. The principle behind this is that higher trophic level organisms have been heavily depleted in ecosystems (Cheung *et al.,* 2002). Initially, the Vs during the fitting

process were allocated from 2.0 to 8.0. After each run, the Vs of each group were checked against the time-series biomass data during the tuning. This methods of estimating Vs produced realistic responses to changes in fishing. Figure 47 shows the average predator vulnerability (AVP) results of the fitted model (including environmental influence), displaying a significant ($P<0.05$) linear relationship with the trophic level. This pattern is in agreement with one of the Back to Future assumptions, which states that large predators (located in higher trophic levels) have a broader spectrum of diet. These top predators (sharks, sierras, totoaba, serranids) are more generalist, and therefore require a longer time to search for food, increasing their vulnerability to predation, including the mortality imposed by fishing (T. Pitcher, 2006 pers. comm.).

A second point to be considered in the pattern of AVPs found could be the decline in biomass of some key potential prey (small pelagics, cephalopods, Sciaenids and rhinobathids) since the 1970s according to surveys by Felix-Pico (1975); Pérez-Mellado (1980); Pérez-Mellado and Findley (1985); and CRIP-Ensenada (1995). Reduced prey abundance could have resulted in an increase in the amount of time for search, increasing their vulnerability to other predators or by fishing gear. This trend of high Vs associated with large predators has been found in other ecosystem models, e.g., in British Columbia (C. Ainsworth, 2006 pers. comm.), and in less intensity in Hong Kong (W. Cheung, 2006 pers. comm.), indicating the need to explore and to quantify this assumption in the future using different trophic models of other marine ecosystems.

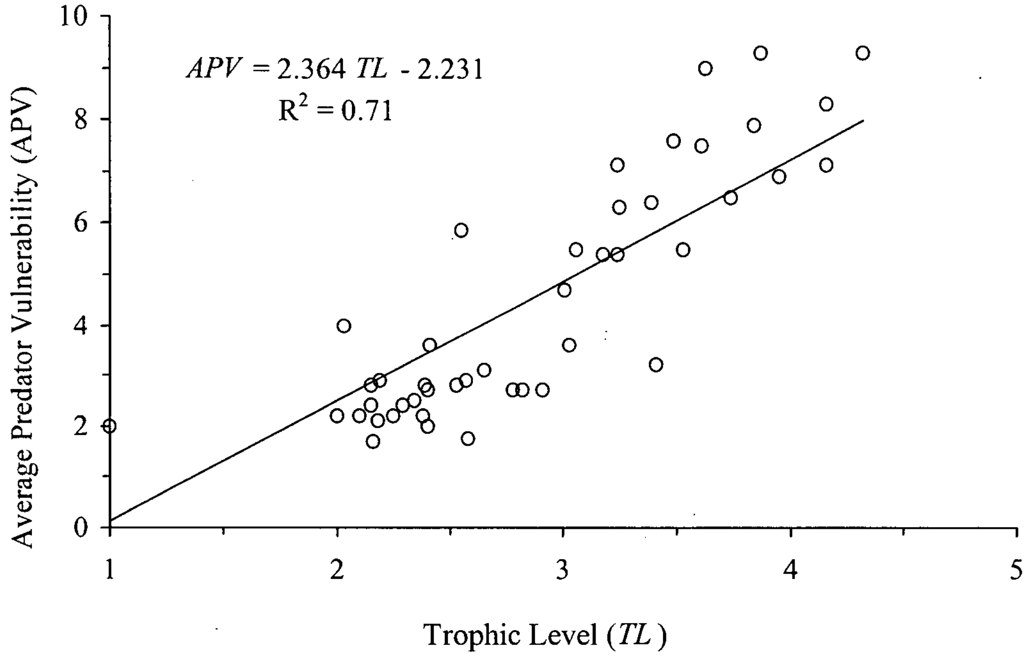

Figure 47. Vulnerabilities resulting from the 1950s model fitted with local biomass surveys, LFK and catches recorded in the upper Gulf that generate a 50-year annual time-series of fishing mortality to fit the 1950s, 1980s and 2000 models. The linear trend observed ($P<0.05$) between trophic level and the average predator vulnerability is in agreement with the assumption that large predators are more generalist and they need longer time searching for food, increasing their vulnerability to predation.

4.2. Exploring ecosystem changes through time: Structure and function of the upper Gulf of California ecosystem in the last 50 years.

One of the main objectives of this project is to quantify the ecological and economic impact of water diversion by Colorado River diversion on the upper Gulf of California. In order to achieve this goal, it is essential to quantify ecosystem states prior to dam construction (Gleen Canyon Dam, 1961), and then to compare them with the current state of the system.

The following sections present trophic structures of the UGC ecosystem for the 1950s, 1980s and 2000 periods (fitted models) which focus on biomass flows among the

components and species of ecological and commercial relevance, with the purpose of identifying parameters that allow for evaluating the impact of the water diversion and fisheries in this marine ecosystem.

4.2.1. Tracking food web changes: Information revealed by trophic levels.

During the last decade, trophic level structures has been used to evaluate fishing and other human effects on marine ecosystems. For example, Pauly *et al.* (1998) demonstrated a steady reduction of the mean trophic level of fisheries landings from 1950 to the present, suggesting that fisheries increasingly concentrate on the more abundant, fast growing fishes and invertebrates near the bottom of the aquatic food web. These findings represent examples of how trophic levels generated by Ecopath models could be used to quantify human impact on marine ecosystems. Trophic levels have been used beyond these generalizations. Thus, Pauly and Christensen (1995), who assigned trophic levels to all fish and invertebrates caught and reported in FAO global fisheries statistics 9Pauly and Christensen (1995) showed that the primary production required (also using transfer efficiencies estimated by Ecopath) to sustain the present world fisheries was much higher than previously estimated: 8% for the global ocean and between 25-35% for coastal shelves, from which 90% of the world catches originate.

In the case of the upper Gulf of California, the estimation of trophic levels and the standard error of these trophic levels (the square root of the omnivory index) estimated from each of the three trophic models constructed were employed to evaluate the changes in trophic structure from 1950 to 2000. The results from the trophic levels aggregation (through the 50 years modeled) indicated a reduction in the number of groups between TL 3.5 and 4.5 (Fig. 48). Simultaneously, there were two more groups within TL= 2-2.4 in the 2000 model than in the 1950s model (Fig. 49). A reduction in the mean TL of the catch from 1950 to 2000 was also observed (Fig. 44), where a decline rate of 0.02 TL· per decade was quantified from 1950-1980 and a 0.1 TL decline per decade from 1980 to 2000. The trend in the reduction of the mean TL of the catch is corresponds to the results reported by Sala *et al.* (2004) that intense fishing in the entire Gulf of California has

reduced the mean trophic level of the landings in the past three decades; this response has also been described for other marine ecosystems associated with intense fishing, and it is known as 'Fishing down marine food webs' (Pauly *et al.*, 1998).

A second result obtained from the analysis of trophic levels aggregation revealed that almost 70% of the living groups considered in the 50-years of simulation could be categorized within TL of 3.0 or lower, indicating that the upper Gulf is a marine ecosystem that has been largely controlled by lower trophic levels, thus supporting the observations reported of Sykes (1937), Félix-Pico (1975) and Pérez-Mellado (1980).

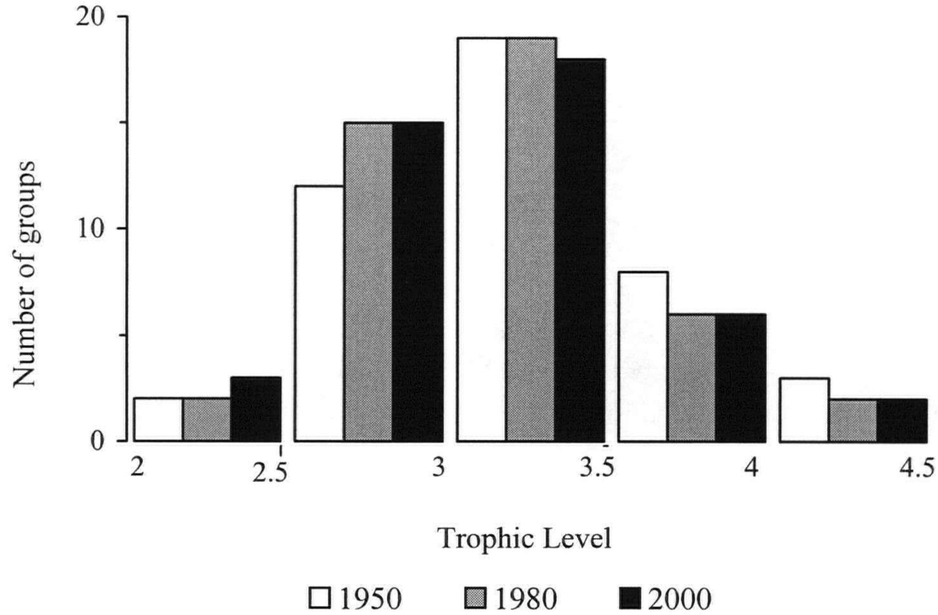

Figure 48. Trophic level aggregation of the 50 groups considered in the 1950s, 1980s and 2000 trophic models of the upper Gulf of California. The results indicate a reduction in the number of large predators (TL of 4 and 4.5) during the last 50 years.

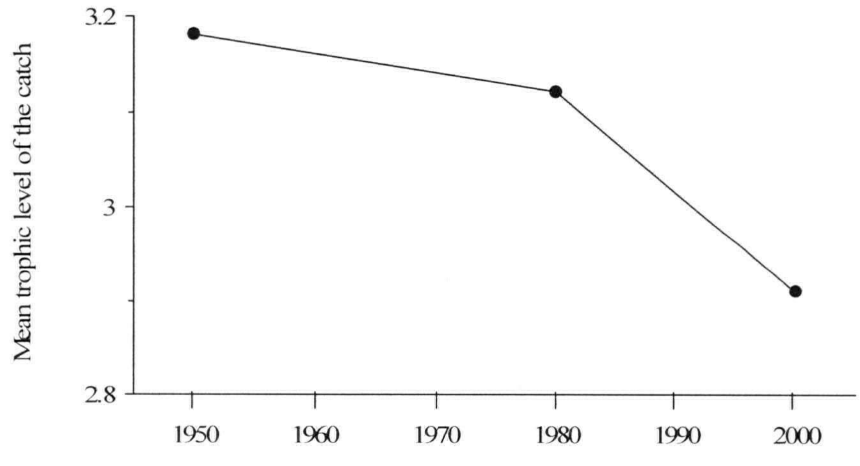

Figure 49. Reduction of the mean trophic level of the catch estimated from the three trophic models of the upper Gulf of California revealing a decline rate of 0.02 TL per· decade was quantified from 1950-1980 and a 0.1 TL ·decline per decade from 1980 to 2000. These results confirmed the Fishing Down in the Marine Food Web trend reported by Sala *et al.* (2004).

4.2.2. Tracking food web changes: The loss of biomasses.

The trophic states of the upper Gulf ecosystem constructed for the 1950s, 1980s and 2000 cover important changes in biomasses over the past 50 years. For example, there was a reduction of 64% in the total estimated biomass in trophic levels 2 and 2.5 (Fig. 50), where most of the groups that occur in this range (shrimps, crabs, chanos, corvinas, croakers) are dependent on detritus food chains, emphasizing the relevance of the Colorado River as a main source of sediments and nutrients in the upper Gulf (Sykes 1937; Mackerel, 1975; Carbajal *et al.*, 1997, Carraquiry and Sánchez, 1999).

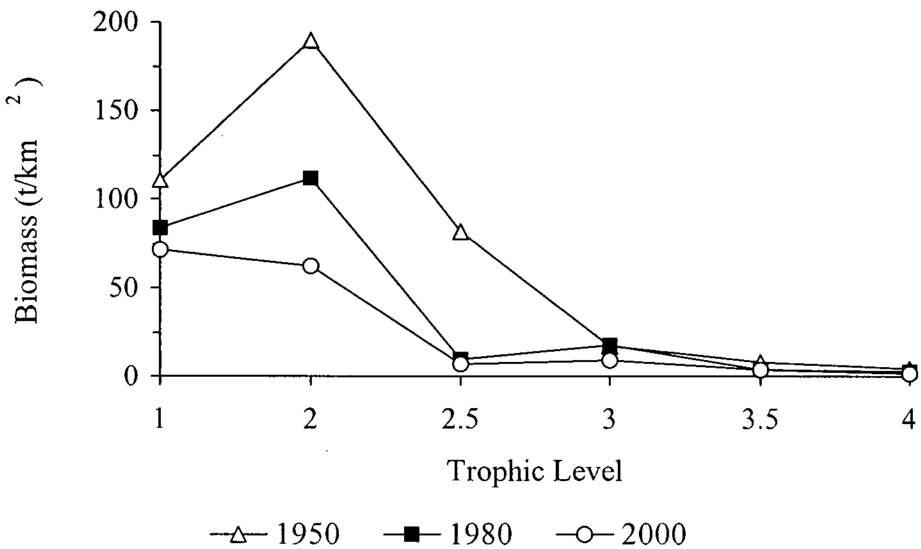

Figure 50. Total biomass by trophic level of the past and present food web models of the upper Gulf of California, displaying an important reduction (64%) of the biomass of organisms located between trophic levels 2 and 2.5 from 1950-2000. Most organisms in this trophic level range dependent on detritus food chains.

The loss of biomass between 1950 and 2000 was experienced not just by detritivores, but also by apex predators of both invertebrates and fish groups. Figure 51 shows the changes in the biomass of the main invertebrate groups. The important role played by commercial fishing extractions in the composition and abundance of the marine biota in the upper Gulf was confirmed by major changes in the biomass of large fish predators such as totoaba and sharks during the last 50 years. Figure 52 shows the changes in abundance from 1950-2000 of the main fish groups from detritivores to top predators. Significant changes were observed. Sharks, declined b y almost 2 t/km^2 between 1950 to the present day, based on the biomasses estimated from LFK interviews. This dramatic decline in sharks in the upper Gulf (Weiner, 2002) correlates with the almost complete disappearance of large sharks and mantas in the Midriff Island region located in central Gulf of California as a response to excessive fishing mortality imposed by industrial and artisanal gillnets and long-liners. More than 200,000 sharks were killed between 1985-93 in the central Gulf of California, and during the mid 1990s, some species of shark (i.e. Pacific sharp nose shark) practically disappeared from the central Gulf (Knudson, 2001; Sea Watch, 2003a,c,d).

The loss of biomass of totoaba is equally dramatic (Fig. 52), a decline, described by the past and present models, which coincided with the collapse of this endemic large predator of the GoC due to a tragic combination of the degradation of their spawning area located in the estuarine waters of the upper GoC because of the diversion of the Colorado River (Arvizu and Chávez, 1970; Sánchez, 1992; Cisneros-Mata *et al.,* 1995; Román-Rodriguez and Hammann, 1995) with intense fishing mortality since the 1930s. The near extinction of totoaba in turn led to bankruptcy of the fishery in 1977 (Flanagan and Hendrickson, 1987; Cisneros-Mata *et al.*, 1997).

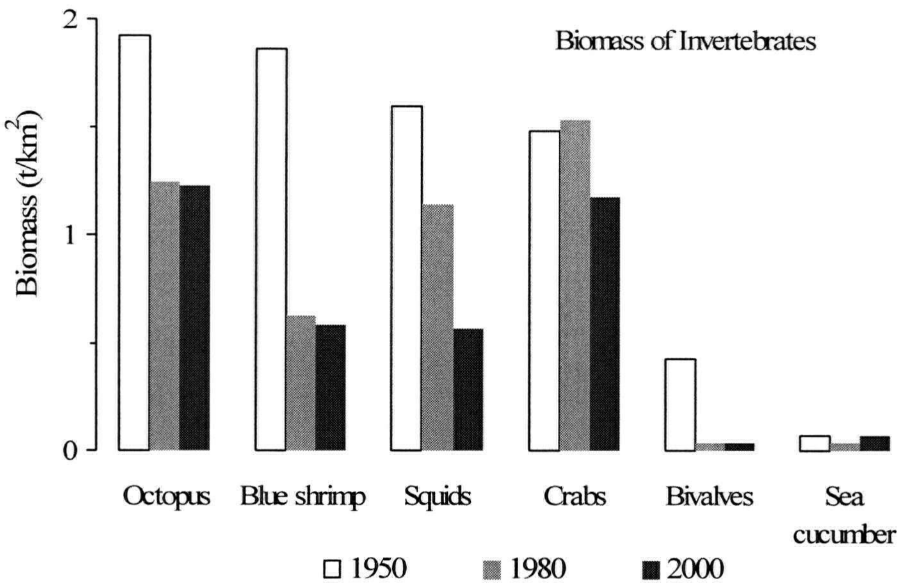

Figure 51. Changes in the total biomass of invertebrates estimated from the 1950, 1980 and 2000 models of the upper Gulf of California.

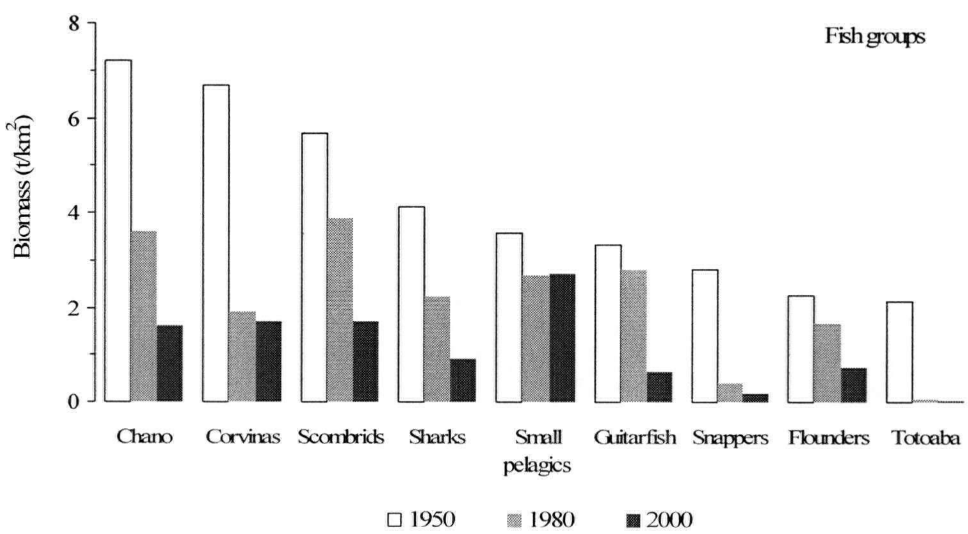

Figure 52. Changes in the total biomass of the main fish groups (including apex predators) estimated from the food web models constructed for the 1950, 1980 and 2000 periods of the upper Gulf of California.

The decline and loss of biomass detected in the invertebrate and fish groups also occurred with the marine mammal groups. Figure 53 presents the changes in the biomass of the four groups of marine mammals showing a general trend of reduction over the past 50 years. The only group that shows a recovery in the abundance estimated is sea lions, no doubt due to the reduction of the predation mortality imposed by a declining population of sharks as a result of intense fishing. The direct impact of fishing on sea mammals has also been documented in the area, where the well known case of the high accidental mortality of vaquita caused by fishing nets has been defined as one of the main reasons for the decline of this endemic species (Turk, 1989; D'Agrosa *et al.*, 1995; Jaramillo *et al.*, 1999; D'Agrosa *et al.*, 2000). Another factor is the deterioration of the vaquita's habitat in the upper Gulf (Silber, 1990; Ortiz, 1999; Campoy, 2001; Urban, 2002). Reasons for this deterioration, include a reduction in the abundance of prey (small fish and invertebrates) combined with the extreme human impact such as pollution and the uses of killer luminescent substances during drug trafficking. In January of 1993, a total of 367 dolphins (most of them *Delphinus capensis*); 51 sea lions (*Zalophus californicus*), 8 whales (*Balaenoptera acuturostrata*, *B. edeni* and *B. physalus*) and hundreds of seabirds were killed (according to tissue samples) by a synthetic cyanide substance classified as NK19, which is used as a luminous marker during drug activities at night in the upper Gulf (PROFEPA, 1995). The increase of sea lion biomass revealed by the trophic models is supported by the local fishers'perception (LFK: Chapter III). According to the survey conducted in 2003, more than 80% of the artisanal long-liners and gillnet fishers interviewed (n=49) mentioned that encounters with sea lions had caused either injuries or severe losses to their catches. These fishers have adopted a new technique of using a small net to distract and feed the sea lions while the long-line or commercial gillnet is deployed. Unfortunately, the expanding population of sea lions in the upper Gulf during the last 10-20 years has increased, thus stepping up attacks by fishers. It appears that marine mammals are steadily losing the fight. For example, from 1990 to 1993, approximately 13% of the 79 stranded mammals (most of them were sea lions) presented signs of injury from either harpoons or bullets (Delgado-Estrella *et al.*, 1994).

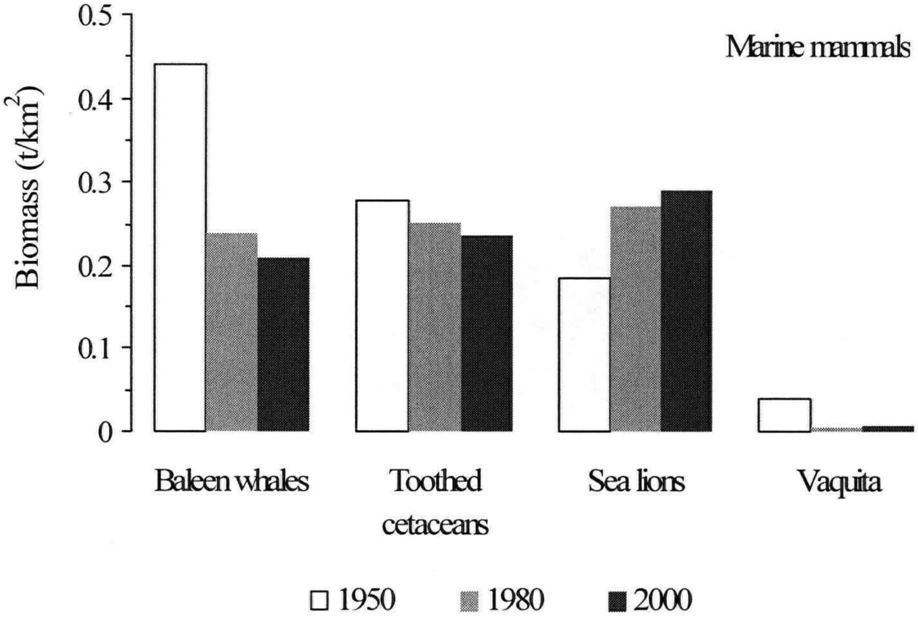

Figure 53. Changes in the total biomass of the marine mammals in the 1950, 1980 and 2000 food web models of the upper Gulf of California.

The temporal analysis of biomasses also show the change in the ratio of benthic over pelagic biomass of the 50 groups modeled from 1950 to 2000 in the UGC. Figure 54 presents a clear trend of reduction in this ratio from 2.8 in the 1950s model to 1.5 in the 2000 model. This indicates an important depletion in the abundance of benthic groups (most of them associated with detritus food chains) since the diversion of the Colorado River at the end of the 1940s. The decline of the non-commercial benthic species in the upper Gulf is a direct result of the damage caused by dams built along the Colorado River and dramatically-reduced flows into the Gulf (Fig 54). Scientific monitoring of this ecosystem before 1975 was scarce (Brusca *et al.*, 2001; Knudson, 2003), and the few documents published on past abundances in the region focused on commercial species such as totoaba and shrimps (Arvizu and Chávez, 1970; Magallón-Barajas, 1987; Brusca *et al.,* 2001). However, the trophic models of the upper Gulf show important changes in

the abundance of those groups which are characterized by either scarce or no scientific facts because they have not been exploited in the area. They do, however, have the potential to indicate changes in the trophic structure of this ecosystem.

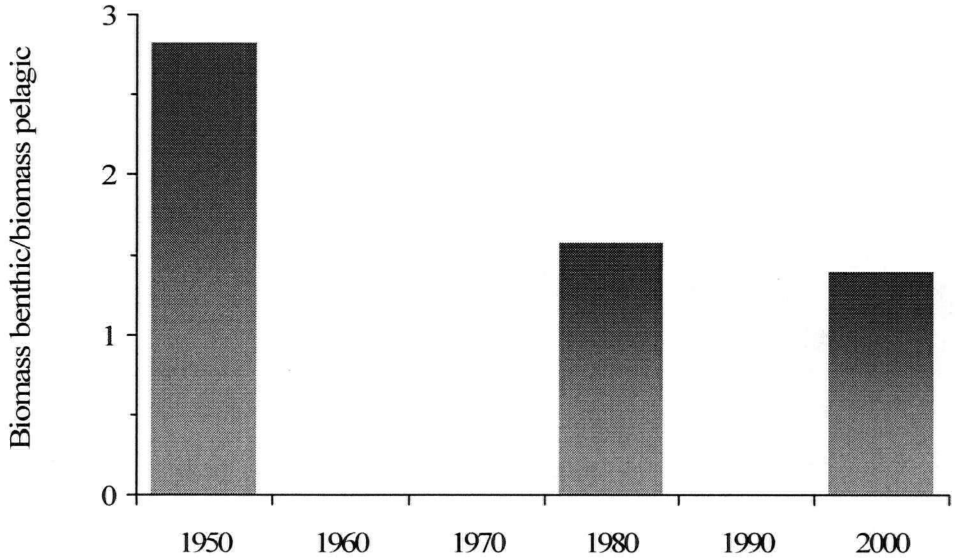

Figure 54. Decline of the ratio between benthic and pelagic biomass of the 50 groups in the trophic models built of the upper Gulf for the periods of 1950, 1980 and 2000.

Loss of total biomass in the low TLs combined with the reduction in the number of large, high-TL predator groups during the last 50 years indicates the effect of two forces acting negatively in the upper Gulf: the practically null input of sediments and nutrients from the Colorado River caused by the dams (affecting detritus food chain organisms), and intense fishing of large fish (sharks, totoaba, serranids), resulting in a 'fishing down in the marine food web' response in the upper Gulf. The changes in abundance and composition of the TL aggregations during the last 50 years in the upper Gulf cannot be explained just by the water and sediment diversion imposed since the 1940s. Other factors such as fishing and probably pollution (including cyanide substances used during drug activities) that may have contributed to these changes, but the high values of EE (>0.4) of detritus found among the past and present models indicates that there has been a high demand of detritus in the system throughout the 50-years modeled.

4.2.3. Tracking ecosystem changes through time: Predation and fishing mortalities.

The previous section presented sharp and continuous declines in the simulated biomasses of invertebrates, fish and marine mammals in the upper Gulf from 1950-2000. These declines may have been the result of two negative forces acting in the area: the degradation of the physical and chemical properties caused by the diversion of the Colorado River, plus high fishing mortality and by-catch pressure imposed by increased fishing in the region. This section examines how fisheries could affect the food web structure (including indirect recruitment aspects) based on the historical reconstruction of the mortality imposed by fishing activities from 1950-2000. The time-series of fishing mortalities were estimated using continuous time-series of biomasses (results from VPA and a series of local surveys conducted by INP) and the official time-series data for catches reported by the government. The details of this 'tuning' process are fully explained in Section 4 of Chapter II (2000 model) and Section 1 of Chapter IV (1980 and 1950 models).

The impact of fishing on the structure of the upper Gulf was evaluated with the multi-species model built for the 2000 period (Chapter II). Results revealed that fishing could be identified as the second top predator (just below 0.204 t/km^2 consumed by large sharks). Also, fishing mortality, spread throughout all trophic levels, indicated that fishing has a large impact on the structure of the UGC in present day conditions. The fishing impact is evaluated in this section in a historic perspective including 50 years of biomasses predicted by Ecosim as a response to the interaction between predation and fishing mortalities. Fishing mortality rates estimated from 1950 to 2000 revealed abrupt changes in the average annual rates, ranging from 0.05 to 1.5 for chanos or from 0.18 to 1.07 for sharks (Fig. 55). The overall trend of the 50-year fishing mortality indicated an intense exploitation of large fish such as totoaba during the 1950's. This exploitation then shifted to sharks in the 1980s and then to small fish such as chanos and corvinas at the end of the 1990s (Fig. 55). This trend caused the two major fishery collapses

experienced in the UGC (totoabas in the 1970s and sharks at the end of the 1980's) as well as the FDMFW trend reported by Sala *et al.*, 2004.

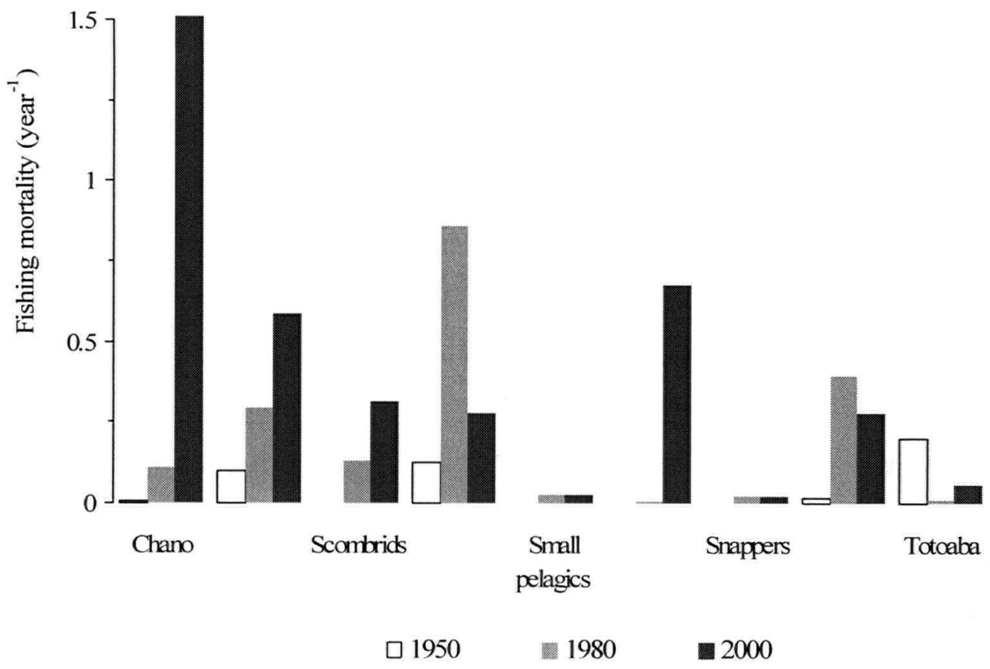

Figure 55. Changes in the fishing mortality in the upper Gulf of California obtained from the past and present trophic models; revealing a shifting of the species fished from large fish such as totoaba and sharks before the 1980s to small benthic groups such as chanos and corvinas.

Another emerging property of the trophic models constructed with Ecopath is the ability to quantify important interactions between predators and their prey through predation mortality. It was calculated by dividing the sum of the consumption of the group i by the other groups over the biomass of the group i (Christensen *et al.*, 2004). Predation mortality was used to evaluate the predation imposed on top predators in the trophic structures of this ecosystem. Sharks, heavily exploited since mid 1960s, had very high rates of fishing mortality that reached their maximum values during the mid 1980s. Unfortunately, these fishing mortalities produced not only the collapse of the shark fishery in the region (Cudney-Bueno and Turk, 1998), but also the virtual disappearance

of Pacific sharp-nose sharks in the area (approximately 200,000 sharks were killed in central Gulf of California from 1985-91; Sea-Watch, 2003b). The decline of sharks in the upper Gulf of California by intense fishing exerted since the 1970s has resulted in the reduction of the mortality of their main prey, sea lions, and a subsequent increase in the biomass of these mammals in the region (Fig. 56). The increased biomass of sea lions predicted by the 2000 model accords with the perspective of 80% of the 49 fishers interviewed in the upper Gulf, who reported an existing conflict with sea lions, confirmed by either the consumption or damage to fish caught. This interaction has reached such a level that guns are used to scare or kill sea lions; from 1990 to 1993, 13% of the 79 stranded mammals (most of which were sea lions) presented signs of harpoon marks or bullet wounds (Delgado-Estrella *et al.*, 1994).

In the case of shark prey (i.e. corvinas, chanos, totoaba, etc,) that also are commercially exploited in the upper Gulf or caught accidentally during fishing activities (vaquita, sea turtles, dolphins), a reduction of their predation mortality rates by the high fishing mortality imposed on sharks (Fig. 57) did not produce the expected increases in their biomasses in the 2000 model. According to the ecology theory, it is possible to experience an increased recruitment of any species when a decline of its apex predator is experienced (Walters *et al.*, 2000). The results from the predator mortality analysis suggest that sharks are currently at low abundance, and they impose a lower predation pressure (compared to that exerted in the 1950s) on species such as totoaba and vaquita. However, the high rate of incidental killing of these species during fishing activities must be reduced in the future in order to recover the size of the populations of these two endemic species to the levels that existed in the upper Gulf 50 years ago. One of the most revealing results of the analysis of the predation mortality was indicated by the potential indirect impact of fishing activities on the trophic interactions among commercial and non-commercial species living in the upper Gulf of California. More details of fishing effects on trophic structures of the UGC ecosystem are displayed by the trophic impact routine included in the network analysis (Section 2.4 of Chapter IV).

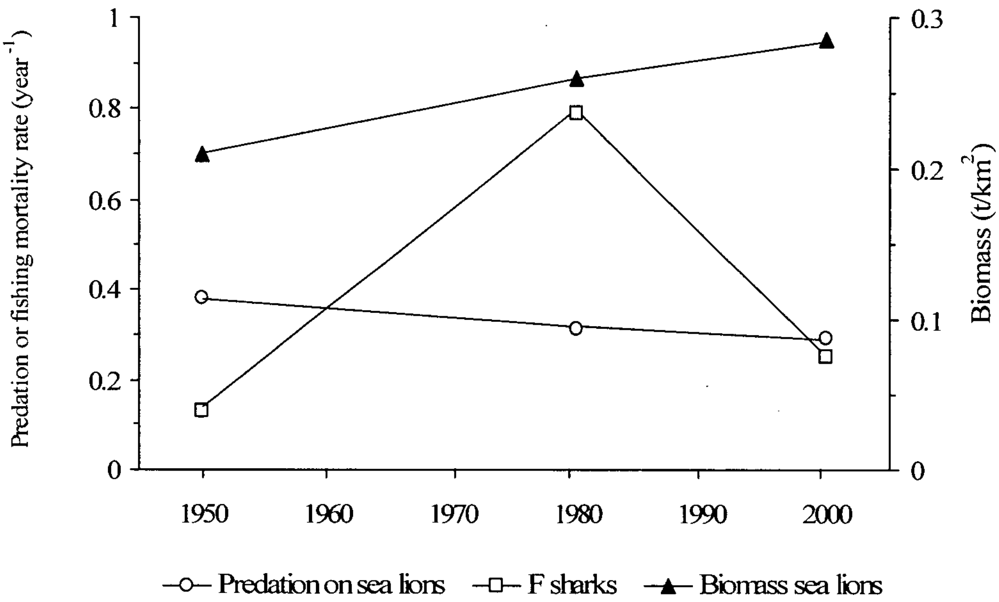

Figure 56. Reduction of the predation mortality of sea lions (circles, left axis) imposed by large sharks from 1950 to 2000. The increased sea lion biomass (triangles, right axis) is attributable to intense fishing imposed on sharks (squares, left axis) since the 1970s.

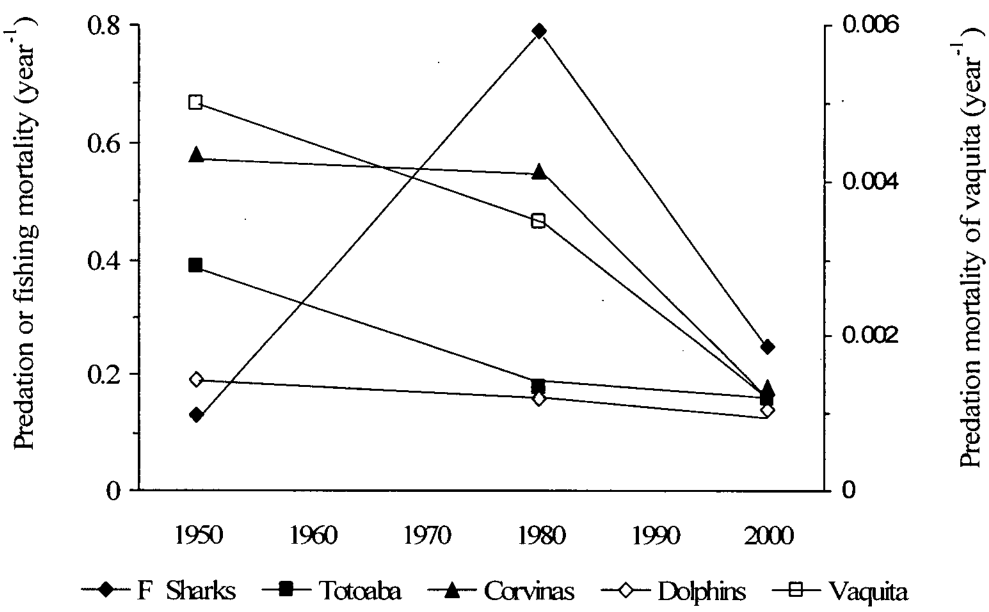

Figure 57. Reduction of the predation mortality rates of the main shark prey (1950-2000) predicted in the upper Gulf of California by the three trophic models. These changes are hypothesized as results of the intense fishing mortality (solid line) imposed on sharks in the area during 1980s, resulting in a sharp reduction of shark stocks and collapse of this fishery at the beginning of the 1990s. Due to the low values of mortality estimated for vaquita, it was necessary to plot their values on the right axis.

4.2.4. Tracking ecosystem changes through time: Network analysis.

One interesting aspect of food webs obtained through Ecopath applications is that they can be used to quantify human impacts through the analysis of the trophic interactions and flows between most groups in the ecosystem, both at the lower part of the ecosystem, where the bulk of the flows occurs, and also to describe what happens at higher trophic levels, especially those that are commercially exploited. There are several ways to evaluate the functioning of an ecosystem, and when Ecopath models are used to describe the structure and function of marine ecosystems, they include the theoretical ecology proposed by Ulanowicz (1986) that quantify attributes of the system related to its development, i.e., detritus recycling and the impact of predation on the system. While this

theory may be in need of revision (Christensen and Walters, 2004); it does represent a way to quantify Ecopath food webs and helps to consolidate knowledge vis-à-vis ecosystem function.

The Ecopath network analysis routine comprises several analyses that quantify the interactions among the groups, *inter alia*, impact of predation, energy flows and recycling of detritus.

The first network approach used to evaluate changes in the UGC ecosystem in the last 50 years was the analysis of the Mixed Trophic Impact (Christensen *et al.*, 2000) which displays the direct and indirect trophic impacts of any group on others in the system. The magnitudes of these impacts are relative, but they are comparable between groups. This analysis revealed that the greatest impacts are caused by the lower trophic levels; for instance, the positive impact of detritus on the upper Gulf ecosystem is noticeable not just in lower trophic groups, but also in the simulated increase of detritus produced indirectly by the increment in the biomass of high trophic levels such as that of totoaba and vaquita as a result of the rise in their prey which is associated with detritus food chains (Fig. 58). Figure 58 gives a quick overview of the importance of detritus in the productivity of the fisheries developed in the upper Gulf in the last 50 years, where the biomasses of species targeted by industrial and artisanal fisheries in the area (ranging in trophic level from 2.0 to 4.2) have been positively influenced by sediments, organic matter and detritus transported by the Colorado River into the upper Gulf. The Mixed Trophic Impact routine (1986; Ulanowicz and Puccia, 1990), was also made it possible to evaluate the impact of industrial and artisanal fisheries. Which can be considered as a 'predator' occupying a mean trophic level of 4.1, slightly lower than that of the top predators, i.e. large sharks. For instance, the last 50 years of fishing and extensive extraction of sharks in the upper Gulf have resulted in a reduction of their impact on sharks from –0.5 to –0.23 which could be interpreted as a decline in competition and cannibalism rates among sharks (Fig. 59).

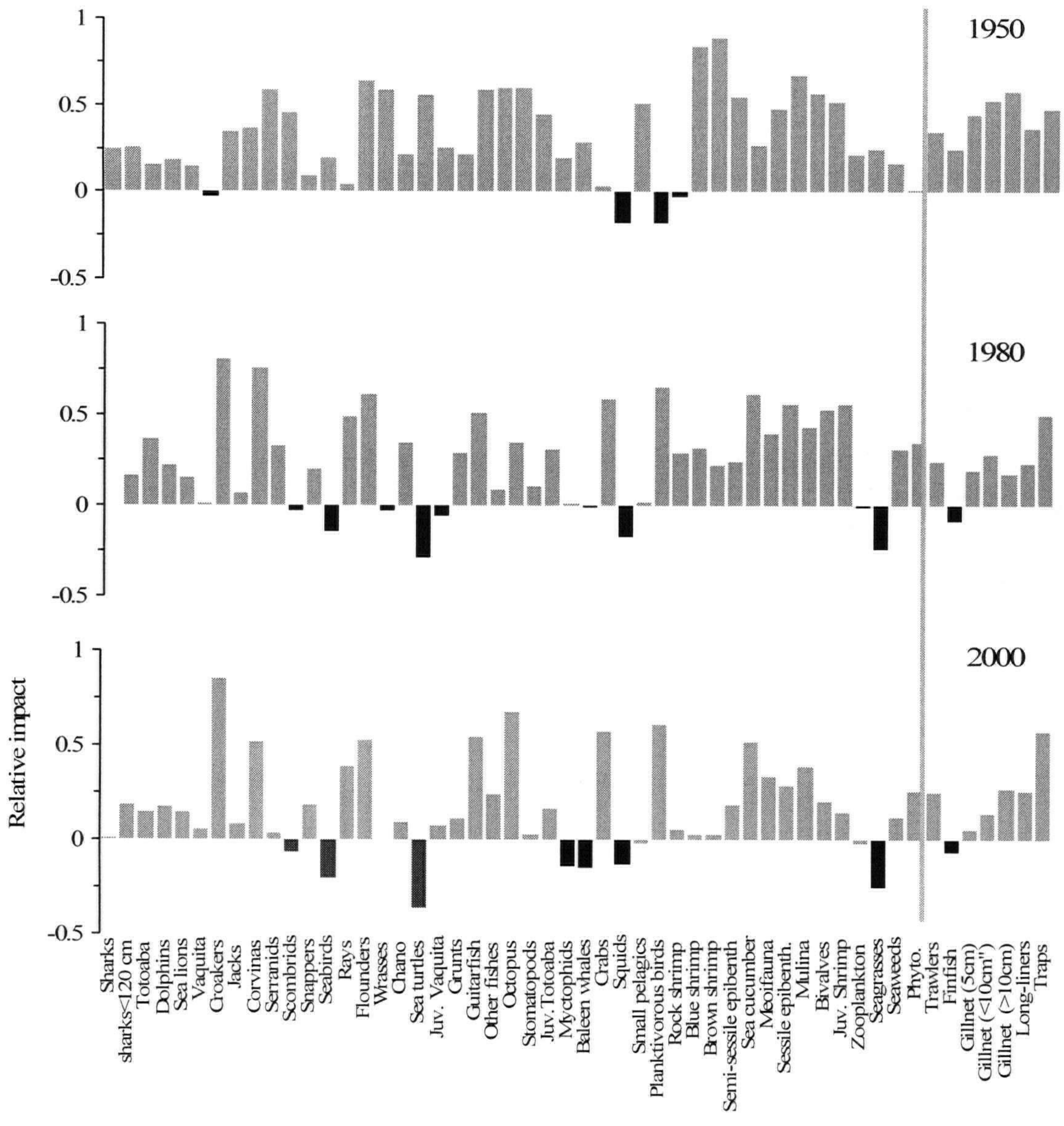

Figure 58. Direct and indirect impacts of simulated increases of detritus on the biomass of the main living groups considered in the 1950, 1980 and 2000 trophic models of the upper Gulf of California. These results reveal the positive impact of detritus on the system, including the theoretical increments in the biomasses of the target species fished by industrial and artisanal gears (last 6 groups on the right). The shaded bars above the x-axis represent positive impacts, whereas the black bars below are negative impacts on the biomasses. These impacts are relative, but comparable between groups. Fisheries are shown to right of vertical line.

Figure 59 reproduces the historical exploitation of sharks documented in the upper Gulf, where the peak of the fishery reached in the mid 1980s, is represented by the maximum value of the Mixed Trophic Impact analysis of -0.44 (long-lines) with a subsequent decrease to –0.31 in 2000 (long-lines). In general, sharks were positively impacted by groups such as sea lions, totoaba, corvinas and serranids, which have been reported as the main prey of shark species in the region (Pérez--Mellado, 1980; Compagno *et al.,* 1995; Compagno, 1999; Morales-Zárate *et al*., 2004). In the case of the endemic totoaba, the results reveal an important reduction in the predation by sharks (>80%) since the 1980s (Fig. 60).

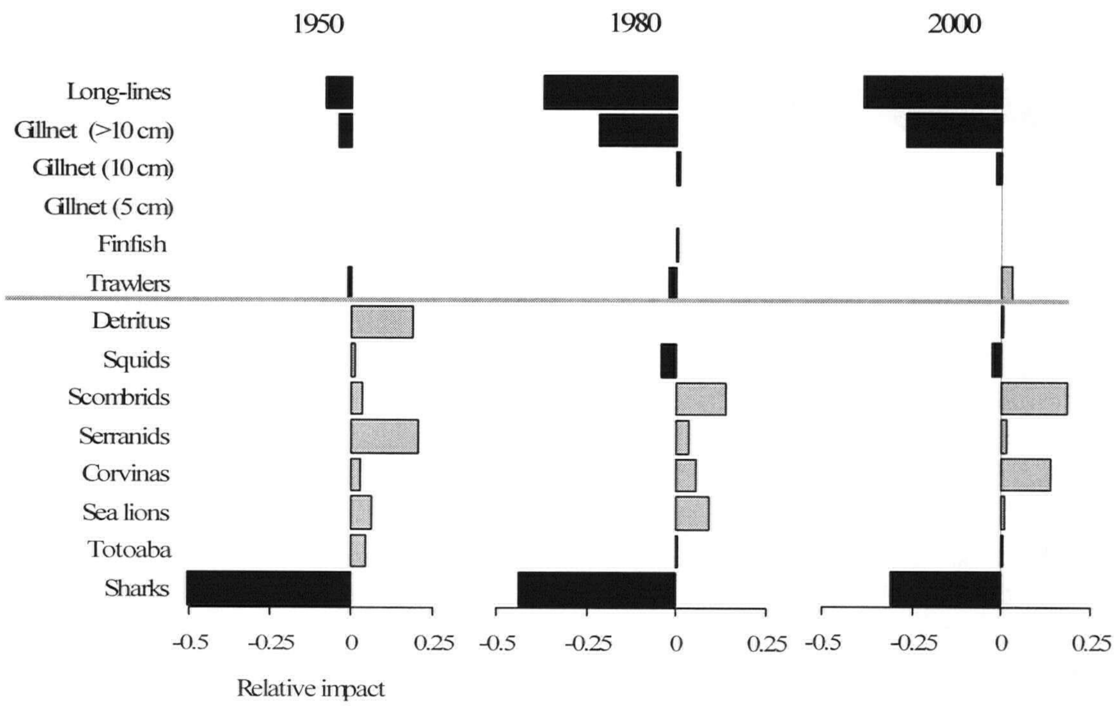

Figure 59. Results from the Mixed Trophic Impact routine displaying the impact of the main groups on sharks, including fishing activities in the last 50 years in the UGC ecosystem. Black bars represent negative impacts (decrease in the biomass of sharks), whereas shaded bars are positive impacts (increasing in the biomass of sharks) as a result of the increment in the biomasses of the groups or fishing mortality (fishing gears) in the y-axis. In general, the negative impact of the long-line fishing on sharks during the last 50 years reproduces the trend of the catches observed for the shark fishery in the area. Fisheries are shown above the horizontal line.

Figure 60 indicates the negative impacts of artisanal gillnets on the biomass of totoaba, considered to be the second highest negative impact on the abundances of totoaba in the 1950s (just behind the predation by sharks). This figure also indicates the trend of declining totoaba culminating in collapse of this fishery at the end of the 1970s (Cisneros-Mata *et al*., 1995; Pedrin-Osuna *et al*., 2001). The positive impacts of long-line fishing on the biomass of totoaba observed in the 1980 and 2000 models are explained by the high fishing mortality imposed since the 1970s on its main predators, i.e., sharks.

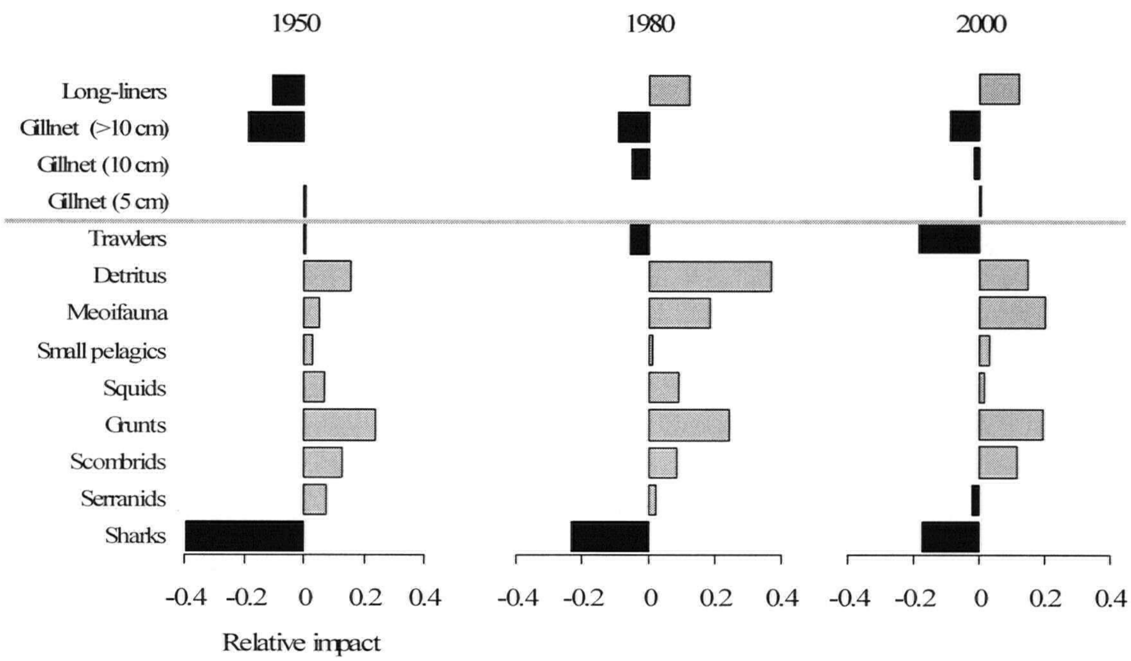

Figure 60. Trophic impacts on totoaba by the fisheries and main groups in the UGC ecosystem in the last 50 years, revealing the negative effect (black bars) caused by intense gillnet fishing. Also it is worth noting the reduction in predation by sharks due to their high mortality imposed by long-line fishing during the 1970' and 1980s. See text for details. Fisheries are shown above the horizontal line.

In the case of the endemic populations of vaquita, the analysis shows a reduction in the predation mortality imposed by sharks in the 1980 and 2000 models, likely due to overexploitation of shark stocks by longliner fisheries. It is worth noting that the negative impact of gillnet fishing on the biomass of these mammals was higher than predation by sharks in the 1950s model, suggesting that by-catch of vaquita has occurred since the beginning of the fishery. The reduction of the impact of gillnets on vaquita in the 1980 and 2000 models could be explained by their legal protection in the upper Gulf, and the use of devices to avoid their incidental killing, plus the fact that the upper Gulf of California has been declared as a Biosphere Reserve (Diario Oficial, 1993; Jaramillo-Legorreta, 1999; Ortiz, 1999; Brusca *et at.*, 2001). Expected positive impacts on the biomass of vaquita (shaded bars in Figure 61) by the groups that they feed on species such as crabs, corvinas, croakers and grunts were observed through the 50 years of trophic modelling in the upper Gulf. It is significant that the main preys of vaquita are species dependent on detritus food chains, indicating the relevance of the sediment and detritus delivered by the Colorado River.

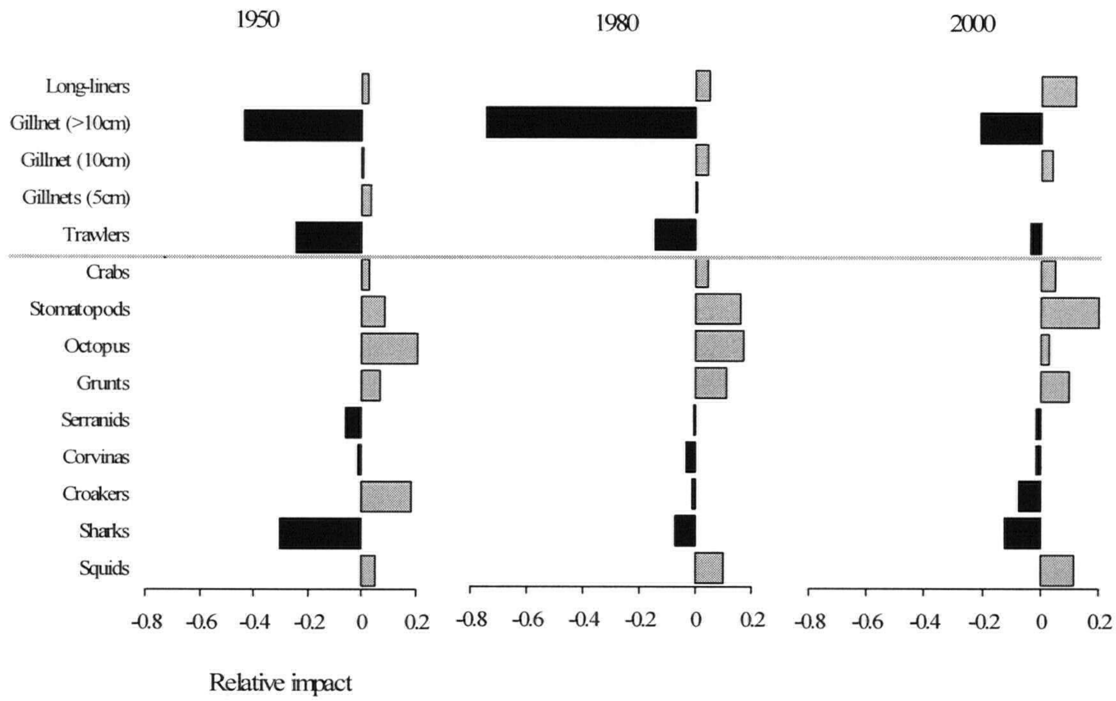

Figure 61. Results from the Mixed Trophic Impact routine indicating both the impact of the main groups and fishing on vaquita during the last 50 years in the UGC ecosystem and the negative effect of gillnet gear on the biomass of these endemic marine mammals. Results also indicate the high predation that vaquita suffered from sharks during the 1950s. Intense fishing exerted on sharks during the 1980s no doubt caused further reduction of this predation. The shaded bars represent the positive impacts of groups such as octopus, crabs, croakers, and grunts that are common prey of vaquita. Fisheries are shown above the horizontal line.

While the network analysis does not produce dynamic or quantitative results, and cannot predict how biomass will change with time or with fishing mortality, it does provide valuable information about the structure of the ecosystem, displaying, in a snapshot, which parts of the ecosystem play a major role. In this section, some network attributes (Ulanowicz, 1986; Ulanowicz and Kay, 1991) are presented to describe holistic properties of the upper Gulf of California ecosystem in the last 50 years. One of the emerging properties of the energy flow indices incorporated into the network analysis is the overhead measure that represents the maximum energy in reserve. Overhead is a measure of the system's ability to withstand unexpected perturbation, an important consideration

in the study of the structure and function of any ecosystem (Ulanowicz, 1986). In the upper Gulf ecosystem, the overhead obtained from the past and present models shows a clear declining trend from 1950 to 2000 (Fig. 62). This trend could be interpreted as a loss in the energy storage contained in the historical hundreds of millions of tonnes of nutrients and organic matter (180 millions tonnes/year; Van Andel, 1964) once deposited every year by the Colorado River, but which ceased at the end of the 1960s due to the construction of the Hoover and Glen Canyon Dams. This result supports the hypothesis made by van Andel (1964) and Cupul (1994) that the upper gulf is suffering an erosional and starvation phase because the sediments and nutrients that were deposited during the pre-dam period have been exported and consumed at similar rates to those before the 1940s.

The (~50%) reduction of Total System Throughput (TST; total flux through the system) in the system from 1950 to 2000 is particularly significant. This is one of the most important attributes of the network analysis because it represents the relative size of the ecosystem, incorporating all the internal consumptions and exports of the system including commercial fishing. The range of the TST obtained from the past and present models in the upper Gulf is 35% higher than an Ecopath model of the Northern Gulf of California that included the upper Gulf and its Delta region (Morales-Zárate *et al*, 2004). Also, they are relatively smaller (~20%) compared to other ecosystems models in the Central Gulf of California and Gulf of Mexico (Arreguín *et al.* 2002; Arreguín *et al.*, 1996).

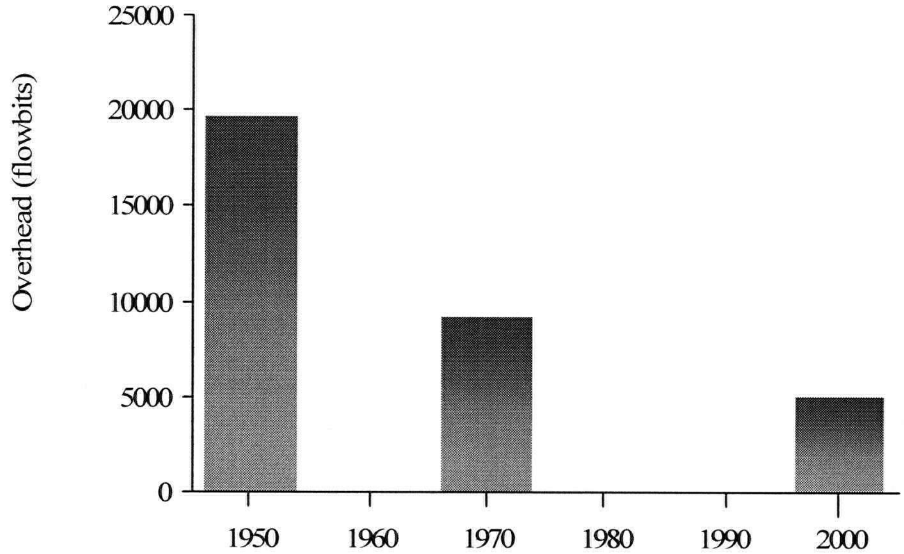

Figure 62. Decline of the overhead measure obtained from past and present Ecopath trophic models of the upper Gulf of California. The overhead measures the energy in reserve in the system and it can represent how the system may meet unexpected perturbation (Ulanowicz, 1986). This declining trend is interpreted as a loss of the energy accumulated in the sediments deposited in the region attributable to huge dams along the Colorado River.

Another key attribute that declined (~50%) over the past five decades in the region was the Total System Biomass (TSB) expressed as t/km^2/year (Table 13), indicating that in 50 years the loss of the average 180 millions of tonnes of nutrients and sediment delivered per year from the Colorado River combined with overfishing practices (i.e. totoaba, sharks and shrimps fisheries collapsed) eradicated approximately 7.7 x 10^5 tonnes for the 4,500 km^2 of the upper Gulf of California and its delta. This observation is supported by other attributes obtained, i.e., the Proportion of Total Flows associated with detritus that also presented a decline of 30%, suggesting a loss in the number of interactions in the lower trophic levels where the detritus food chains dominate. This hypothesis is supported by the decline in the proportion of the biomass of benthic and pelagic groups over the last 50 years, indicating that groups directly affected by detritus and nutrients delivered by the Colorado River have declined in abundance. This trend reproduces the history of many benthic species, e.g., endemic populations of clams were reduced to 5%

of pre-dam abundances (Kowaleski *et al.*, 2000; Rodriguez *et al.*, 2001).

A second perspective provided by the network analysis was a general framework of the structure and changes of fisheries among the three trophic models. These results are summarized in Table 13. A key result of this analysis is the reduced trophic level of the catch recorded in the upper Gulf during the last 50 years, during which a loss of 0.25 TL was estimated by the models (Table 13). This trend accords with the average reduction in the trophic levels of catches recorded for the entire Gulf of California since the 1970s. This reduction is the result of an intense fishing mortality that gradually shifts the catches from a long-life high trophic level species to that of a short lifespan species (Sala *et al.*, 2004). This result confirms that the industrial and artisanal fisheries in the upper Gulf are negatively impacting this ecosystem, including the near extinction of totoaba from over-fishing (Cisneros-Mata *et al.*, 1995; Román-Rodriguez and Hammann, 1997) and the high incidental mortality of vaquita due to gillnets (Jaramillo-Legorreta, 1999; D'Agrosa, 2001).

Sala *et al.* (2004) concluded that the coastal fisheries of the southern Gulf are unsustainable and that management needs to be re-evaluated in order to prevent further degradation of coastal food webs. These suggestions are supported by the results obtained in this section and they can easily be extended to the upper Gulf of California. The intense mortality imposed by the multiple fisheries developed in the upper Gulf in the last 50 years was also indicated by the increasing trend of the total catches obtained from the network analysis of the past and present models. An increase of almost 300% in the total catch was estimated in the period modeled, representing an increase in the total extraction of marine resources of almost 35,000 tonnes per year for the entire upper Gulf during the 2000s over catch levels in the 1950s (Table 13).

Table 13. Flow indices of the upper Gulf of California ecosystem based on the results of the Network Analysis applied in the three trophic models constructed for the 1950, 1980 and 2000 periods.

Ecosystem attributes	1950 model	1980 model	2000 model	Change	Remarks
Total System Throughput ($t/km^2/year$).	12,106	8,132	5,922	- 48 %	Relative size of the system (better than the sum of the biomass).
Overhead ($t/km^2/year$).	13,024	9,417	5,998	- 46 %	Maximum energy in reserve and how the system can meet unexpected perturbation.
Total System Biomass excluding detritus ($t/km^2/year$).	347	233	176	- 49 %	Could the nutrients delivered by the Colorado change the carrying capacity?
Proportion of total flows originated from detritus.	0.32	0.26	0.23	- 32 %	Relevance of Colorado River as main source of detritus accumulation.
Ratio of biomass of Benthic/pelagic groups.	2.73	1.57	1.43	- 52 %	Reduction of groups directly affected by detritus & nutrients from CR (i.e. clam population was reduced to 5% of abundance).
Total catches. ($t/km^2/year$).	3.5	13.4	12.1	+ 300 %	10-15% of Mexico total landings originated in the UGC
Mean Trophic Level of the Catch.	3.14	3.09	2.89	- 0.25 TL	Intense fishing pressure, suggesting FDMFW.

Examining fishing and climate effects on the upper Gulf of California.

Chapter IV illustrated how past and present models can be used to explore how single functional groups affect form and structure of the upper Gulf of California ecosystem. These changes can then be used as a first approach to quantify ecological impacts attributable to diversion of the Colorado River.

Although the Back to the Future approach adopted in this research entails reconstruction of past ecosystem states of the UGC, it also emphasizes the potential of the dynamic simulations to explore changes in the UGC as a result of either natural factors (influence of climate) or human influences (habitat destruction or effects of fishing). Using this new methodology, this Chapter sets out to explore the influence of climate, ocean change and fishing on the marine ecosystem of the UGC. Understanding the effects of these three factors in marine ecosystems (not just in the Gulf of California) may not only allow us to forecast ecological and economic impacts more rapidly, but also simultaneously develop more robust policies against climate and ocean change. To this end, the second part of this Chapter includes various types of climate forcing functions to explore the role of climate change in the upper Gulf of California.

5.1. Exploring ecosystem effects of changes in fishing effort under different policy objectives.

Two main aims in building present and past upper Gulf of California models were to explore the effect of changes in mortalities imposed by fishing fleets operating in the area, and to investigate possible optimum fishing strategies under specified economic, social and ecological objectives. Dynamic simulations (changes of fishing mortalities over time) based on trophic models can guide decision makers as to which directions they can take in future management plans, but are of course subject to all of the uncertainties associated with such models.

The fishing optimization presented in this Chapter is an exploratory approach to maximize four of the critical 'objective functions' considered for management of marine ecosystems defined in Ecosim (Christensen *et al.*, 2004).

(1) Maximize fisheries rent, i.e., profits from sale of catch (each species has a market price) after deducting the costs of fishing (both fixed and variable). The objective is to focus on the fishing efforts of the most lucrative species. Appendices 7 and 8 present the market price used for each commercial species and the fixed and variable costs for the fleets used in the optimization.

(2) Maximize social benefits, defined here as direct employment in the fisheries. For each gear type or fishery sector, the number of jobs per catch value is specified in the model, and the optimization favors the most labour intensive gear. The benefits of this objective are calculated as numbers of jobs relative to the catch.

(3) Maximize rebuilding of species: this objective reflects the external pressure on policy makers and stakeholders to preserve or rebuild the population of charismatic or indeed any given species. Fishing mortalities across gear types are adjusted to maximize the biomass of groups that receive a high weighting value from the user, in this case, it focused on the rebuilding of the two endemic species that are endangered in the UGC: totoaba and vaquita. The biomasses used during the optimization corresponded to those incorporated into the 2000 EwE model.

(4) Maximize ecosystem structure or 'Ecological'. This objective is based on the network analysis presented in Chapter III and it refers to the ecosystem 'maturity' concept described by Odum (1971 and 1988) in which mature systems are dominated by large, long-lived organisms. Optimization for ecology often implies a reduction in the fishing effort for all gear types in order to maximize the biomass of the groups that receive a user-set weighting value (Christensen *et al.,* 2004).

The fishing optimization search also allows the modeler to specify the weights for one or more of these objective functions, based on the management priorities established for each scenario. Basically, by changing relative fishing mortalities, the multi-dimensional Davidson-Fletcher-Powell search algorithm included in the *Ecosim* 'policy search' routine will seek an optimum solution based on the weighting assigned to the objectives (Walters *et al.,* 2002; Christensen *et al*., 2004). The search iteratively changes the fishing mortality of all the gears employed (a total of six for the 2000 model) to maximize the objective specified (or a mix of the four objectives) over a simulation of the 50 years.

The catches (including estimates of illegal fishing), discards, fishing efforts, relative operating costs and market prices used in the mass-balanced model of the UGC for present day conditions were incorporated into the optimum fishing routine built into Ecosim (Christensen *et al*., 2004) and run for 50 years (also, this model was calibrated with a time-series of fishing efforts; see details in Chapter II). The optimum search maximizes the chosen objectives and provides a forecast of economic values, numbers of jobs, catches and biomasses at the end of the 50-year runs for all the groups exploited in the ecosystem. Some scenarios resulted in drastic depletions of vaquita and/or totoaba, and in extreme cases, their extinction (vaquita) or extirpation from the upper Gulf (totoaba). Assumptions, uncertainty of the results and the practicality of implementing any reduction of the fishing effort in the UGC are discussed at the end of this section.

Using the 2000 landings, discards and fishing mortalities of the upper Gulf as a starting point, important changes in the total mean catch (all commercial groups) were found after the 76 scenarios were run under a 50-year simulation. Figure 56 shows the theoretical tradeoffs between extreme scenarios where no fishing was allowed (high weighting on rebuilding or ecological objectives) or those cases where excessive fishing efforts were employed without considering the depletion of charismatic species (scenarios with high values on economy and number of jobs). This was as expected, because economic and social, as opposed to ecological weightings, were assigned to maximize catches.

However, a few scenarios which focused on ecological attributes, for example scenario number 53 (Appendix 8), a achieved a hypothetical harvest of up to 0.6 $t/km^2/year$ greater than that of the present landings (Fig. 63). Although this scenario emphasized the ecological objective, it was run with the same fishing efforts for each gear type employed in the 2000 mass-balance model. For this reason, scenario 53 was considered a 'realistic' option as opposed to two other scenarios with the potential of higher harvests than those of 2000 were considered as unrealistic because they were designed with no fishing (zero value as the economic objective).

A similar pattern was found in the hypothetical catch obtained under the rebuilding goal, where only scenario 51 predicted a catch 0.3 $t/km^2/year$ higher than that estimated in 2000 under the same fishing efforts (score 1 in economic objective), but which emphasized the recovery of totoaba and vaquita). It is noteworthy that only 2 out of the 44 ecological and rebuilding scenarios tested produced harvests slightly higher than the catches estimated in 2000 with the same fishing efforts as those of the 2000 model. The original goal of this exploratory analysis was not to incorporate the results from the scenarios described above into future policies for the management of the fisheries in the region, instead, these 'win-win' scenarios (i.e., scenario 53) simply represent a preliminary stage and they must be taken as an exploration exercise which indicates that both conservation and sustainable fisheries could reach their goals. Future detailed analyses of the win-win solutions must be conducted in order to get more solid and realistic options that could set the basis for long-term policies which would include both restoration of endangered species and viability of the fishing sectors.

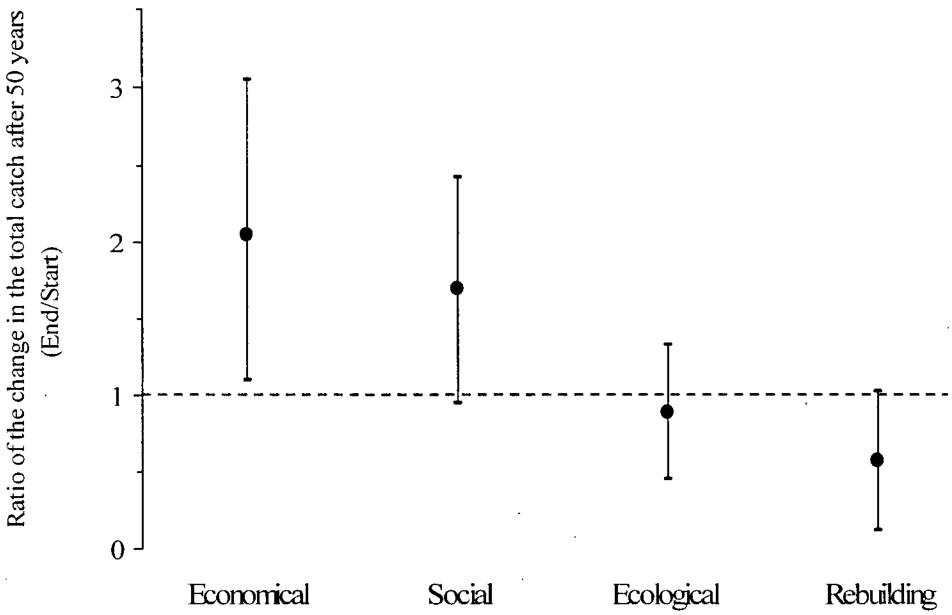

Figure 63. Mean change in total catch between the 2000 model and those forecast 50 years later in the upper Gulf of California (expressed in $t/km^2/year$). The dotted line represents the 2000 total catches estimated in the region. The simulation was run under four major criteria employing 76 different scenarios in order to explore optimum fishing strategies (see text for details). Error bars represent standard deviation.

Using the 2000 market prices ($US/kg; Appendix 6) and operating and fishing costs as detailed in Appendix 7, it was possible to calculate the mean change in profit after the 50-year ecosystem simulation under the 76 scenarios considered (Fig. 64). The observed trend met with the expectations, i.e., economic and social fields must be the most profitable objectives whereas restoration and rebuilding objectives were predicted to be less profitable (in comparison with the value obtained for the commercial fishing entered in the 2000 model). Even though the ecological scenarios were less profitable than the economic and social goals, a few of them (i.e. scenario 47) resulted in theoretical profits higher than those estimated in 2000; however, they were considered unrealistic because of the proposed drastic reduction in fishing. Also, it is worth noticing that the mean profit of the rebuilding objective (including specific scenarios for vaquita, totoaba and the

entire ecosystem) was lower than the current profits and that only scenario 76 produced profits above the 2000 model (upper limit of standard deviation of the mean profit of the rebuilding objective, Figure 64); it is, however, considered unrealistic due to its properties (zero values in economic and social objectives).

Figure 65 displays the relationship between the rebuilding of vaquita and the total biomass of the upper Gulf (excluding detritus), suggesting that recovery efforts and plans for this endemic marine mammal could also result in an increase of the overall biomass of the region. This recovery is explained as a direct result of a reduction in fishing pressure, but there were scenarios that could match the economic conditions used at the start of the 50-year simulation (Fig. 65). It is important to mention that several restrictions and simplifications were adopted during the simulations and the win-win scenarios obtained are far from the real conditions. Further analysis and local scientific and fisher's input into scenario interpretation is needed before incorporating into management policies. Fisher's participation is critical to their compliance with any future management regime. On the other hand, Figure 66 exhibits a negative (but non significant) trend between profit and the recovery of vaquita. This negative trend is explained by all the restrictions imposed on the fleets operating in the upper Gulf in addition to the high mortality imposed by incidental killings (gillnet fleets) and the depletion of potential prey caught by this marine mammal. Considering just the economic value and profits, the recovery of the vaquita population to double its current level as a result of closing the fisheries could lead to a loss in profits of up to \$0.61/kg/km^2 (54%). This theoretical exercise illustrates the complexity in choosing ecosystem restoration goals; the social component and sustainable fisheries are elements that could not be excluded from any realistic restoration goal.

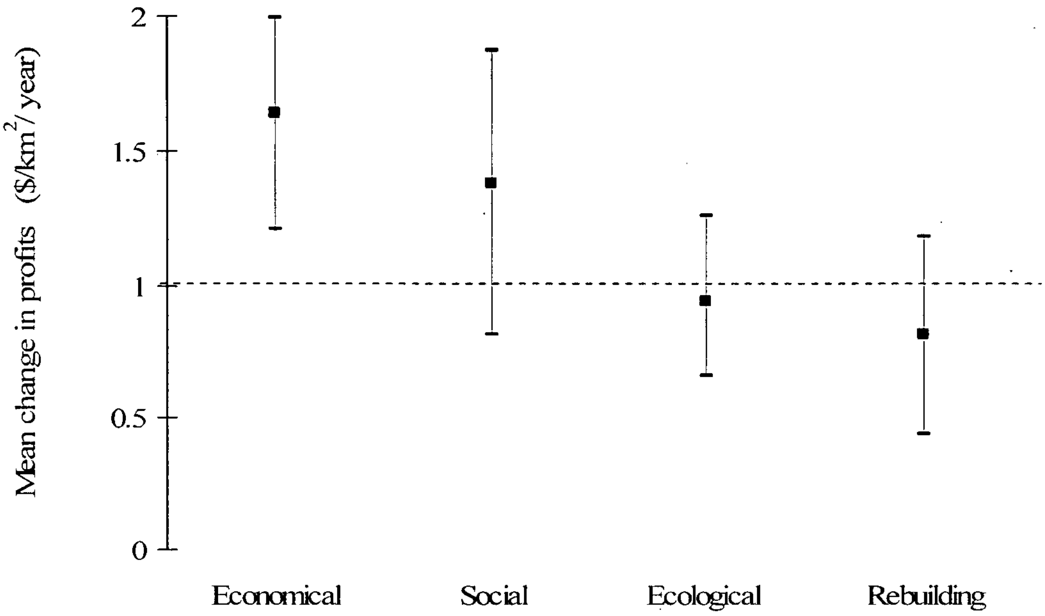

Figure 64. Mean change in the profit obtained from commercial fishing ($\$US/kg/km^2$) between the catches of 2000 in the upper Gulf of California and those forecast after 50-years of ecosystem simulations. The dotted line represents the value of the catch at the start of the simulation (see text for details). Error bars represent standard deviation.

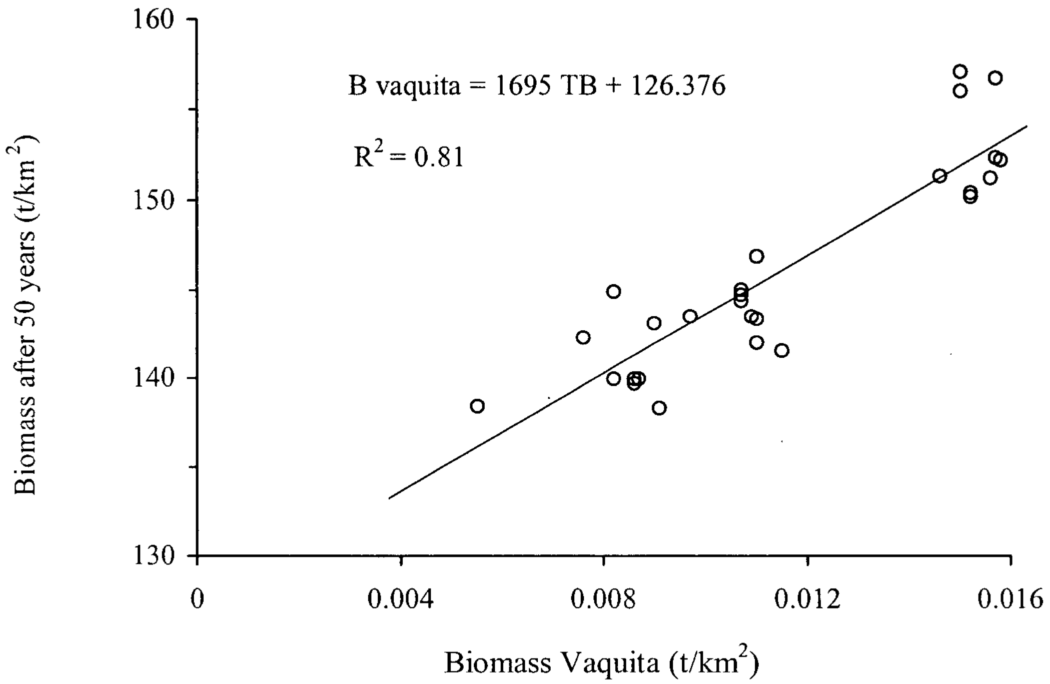

Figure 65. Relationship between the restoration goals for vaquita with the total biomass of the upper Gulf of California ecosystem (Y-axis) and the biomass of vaquita after a 50-year simulation. This simulation considers only restoration and rebuilding objectives (34 scenarios), but shows that conserving efforts to preserve vaquita could achieve an overall rise of the biomass in the region (This significant relationship <0.05 is displayed by the line).

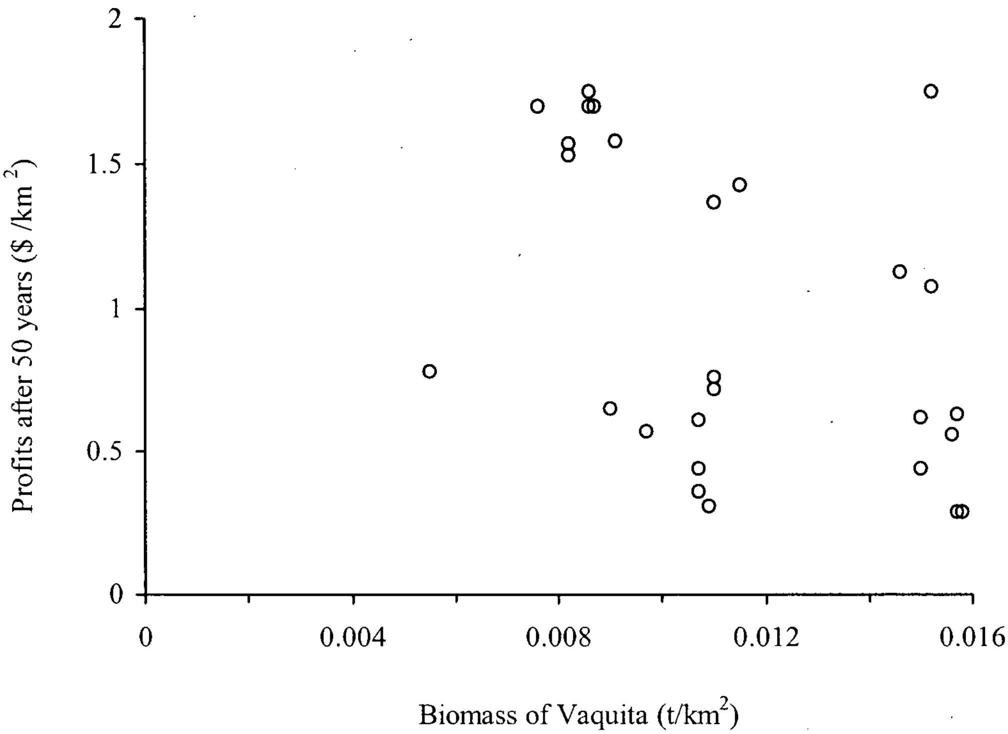

Figure 66. Relationship between the profits ($US) predicted after 50 years of simulated fishing in the upper Gulf of California (industrial and small scale fleets) and the recovery of the population of the endemic vaquita. The negative trend displayed (non-significant) that the profits decreased as the biomass of vaquita increased, and it agrees with that which was expected due to a reduction in fishing efforts.

5.2. Exploring changes in biodiversity under different fishing strategies.

Quantifying changes in biodiversity across scenarios is another critical component to include in the policies and strategies of managing marine ecosystems. This exploratory analysis used the Q-90 biodiversity index for comparison among the 76 scenarios designed. Q-90 is a modified Kempton index (Ainsworth and Pitcher, 2006), designed to be used specifically in trophic models generated by Ecopath. Q-90 measures the effects of the different fishing strategies on whole ecosystem biodiversity, through the changes in the slope of the cumulative curve between the 10 and 90 percentiles (Fig. 67). The main

modification of Q-90 is that each functional group is considered a single species where biomass is analogous to the number of individuals, a vital element to estimate richness and biodiversity (i.e., Shannon-Weaver/Simpson index; Margalef, 1968). This methodology avoids extinctions by maintaining the same number of functional groups; but sets a low non-zero for scenarios with critical depletion (high weights on economic objectives). To increase the sensitivity of the index to group depletions, a filter is passed over the biomass profile during each year of the simulation (Ainsworth and Pitcher, 2004). For this exploratory analysis, an 80% filter was adopted, meaning that if a biomass of a given functional group falls below 80%, that group is omitted from the Q-90 calculation and it will result in a reduction of the measured biodiversity of the system.

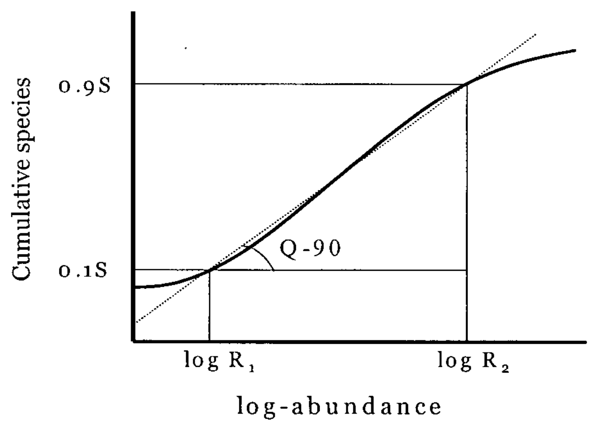

Figure 67. Measure of biodiversity with Q-90 index modified from Kempton and Taylor (1976) for trophic modelling of marine ecosystems (Ainsworth and Pitcher, 2004). S represents the number of functional groups (analogous to number of species) in the reference model; R_1 and R_2 are lower and upper 10 percentiles of the species abundance distribution. Figure courtesy of Ainsworth and Pitcher (2004).

Using the changes of this biodiversity index, it was also possible to explore the relative ecological impact of different fishing strategies. This methodology was designed to support the use of marine ecosystem modeling to find optimal fishing strategies. The incorporation of biodiversity into the search for optimal fishing will increase the likelihood of obtaining more realistic restoration targets that satisfy multiple (social and economic, ecological) management objectives.

Using this methodology, Q-90 index was calculated for each of the 76 scenarios that included economic, social, ecological and rebuilding objectives. As explained in Section 5.1 (an economic objective maximizes profits, a social objective maximizes employment, an ecological objective increases the biomass of long-lived species and a rebuilding objective includes risk aversion for specific species; Walters *et al.,* 2002), these objectives span the spectrum of human use *versus* conservation, and include both total fishing with no consideration of the ecology and no fishing in the upper Gulf.

Figure 68 shows the relationship between the biodiversity measured by the Q-90 index and the value of the catch (expressed in $US/km^2/year) after a 50-year period of simulations for the 76 scenarios categorized by social, economic, ecological and rebuilding criteria. After 50 years of simulation, none of the 16 economic scenarios tested produced a higher biodiversity than 2000 (Q-90 = 5.1); however, they were the most profitable ecosystems (in terms of the value of the commercial species). As expected, rebuilding and ecological objectives produced the highest biodiversities in the long-term, reaching up to 10% more biomass for the total ecosystem in comparison to that calculated in 2000 in the upper Gulf. It is remarkable that, at the end of the 50-year period of simulation, only seven out of 76 scenarios produced both biodiversities higher than 2000 and theoretical harvests and commercial value above the 2000. The majority of these scenarios were considered unrealistic because they implied total or drastic reductions to the fisheries in the region. However, scenario 53 (Appendix 8) was the only one that simultaneously considered the same fishing efforts as 2000, and at the end of the run, produced a 'win-win' ecosystem because its biodiversity and catch value were higher than those at the start of the dynamic simulation.

The biodiversity resulting from the 50-year simulations of the 76 scenarios produced consistent results according to each of the four objectives implemented. For example, under the monetary value ($US), the biodiversity produced by the rebuilding scenarios was more comparable and closer to that obtained under the economic goals (Fig 68). For this reason, a hierarchical clustering analysis was employed to categorize the 76 scenarios based on Ward's minimum variance method (ANOVA sum of squares between Q-90 and $value at the end of the simulation) to estimate the minimum distances between single linkages. Figure 69 shows the cluster dendogram in which economic scenarios were clearly separate from ecological and rebuilding scenarios. The results show that the four objectives employed in the search for optimum fishing undoubtedly produced statistically different outputs that were in agreement with the different weights used under the economic, social, ecological and rebuilding goals.

The overall results of this exploratory analysis confirm that fishing and conservation could be compatible, but the low number of scenarios with this 'win-win' characteristic suggests a high risk for endangered vaquita and totoaba. The Mexican government's current management policies for the upper Gulf chiefly focus on conservation and controlling the size of the fishing effort. These policies are in general agreement with the win-win scenario criteria for long-term sustainable fishing in the region. In this way, fishing effort in the Gulf of California has been regulated efficiently at least since early 1990s when the first steps by the Mexican government were taken to create effective systems of licensing and permits, creating Biosphere reserves, incorporate accurate fishing seasons, establishing mandatory turtle excluder devices in commercial shrimp trawlers, createe committees for the recovery of endangered species (i.e., vaquita and totoaba), use the Mexican Navy to police the outlaws and one of the most important regulation was to createe in 2000 the National Fisheries Chart (CNP) to avoid the increasing trend of fishing efforts.

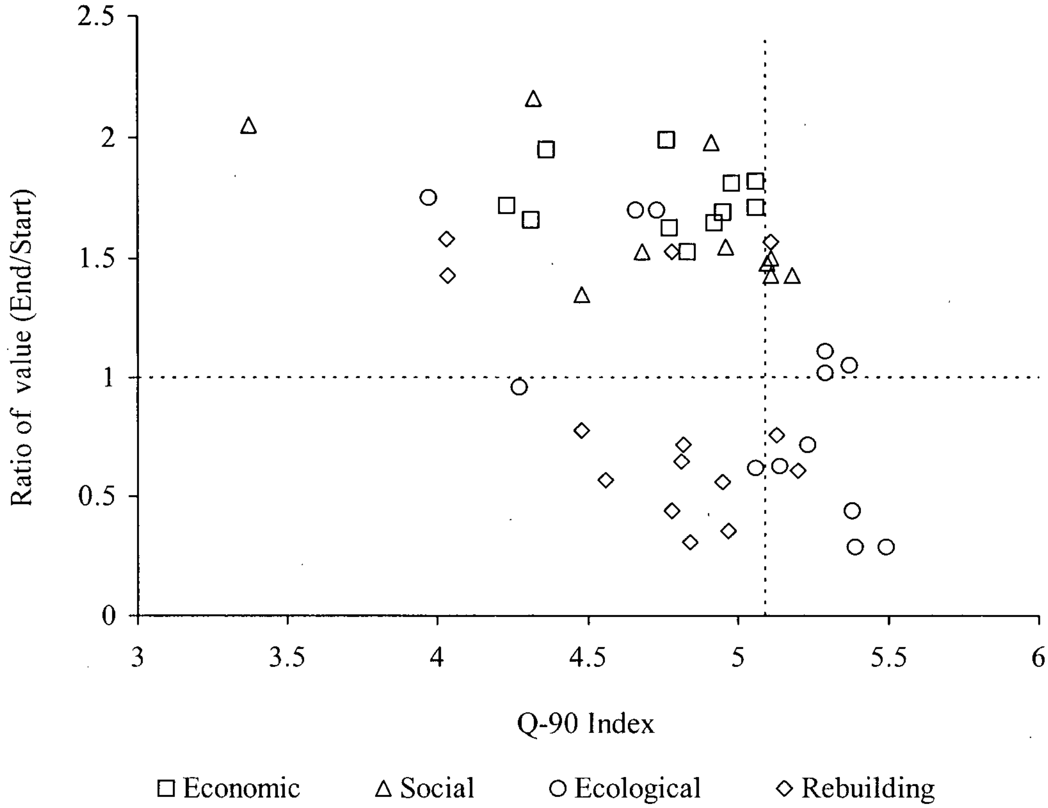

Figure 68. Relationship between the biodiversity measured by the Q-90 index and the final value of the catch (expressed in $US/km^2/year) after 50 years of simulation under economic (square), social (triangle), ecological (circle) and rebuilding (diamond) criteria. Horizontal and vertical dotted lines represent the 2000 model values at the start of the simulation.

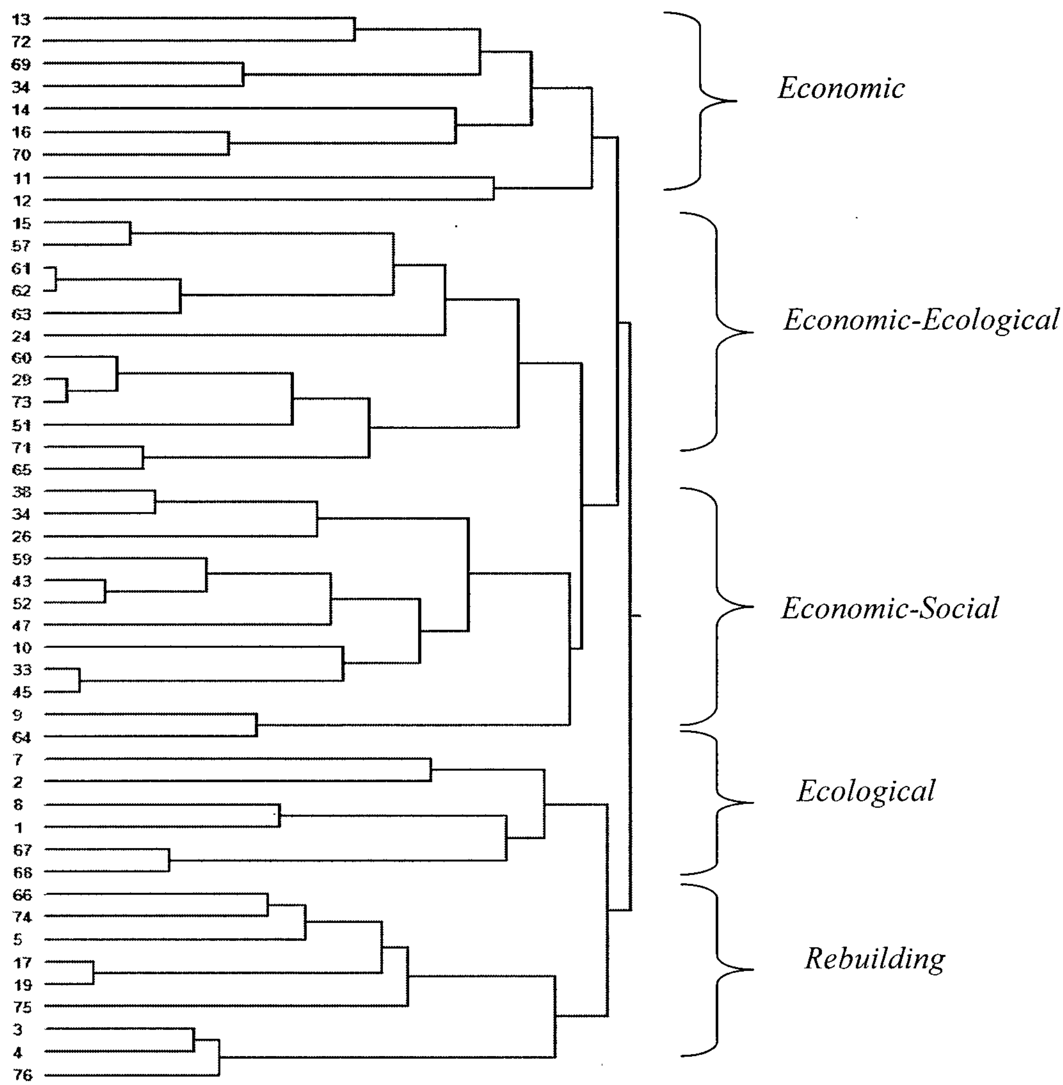

Figure 69. Cluster dendogram for the monetary value (based on market prices) and biodiversity index (Q-90) of the 75 scenarios of fishing optimization in the UGC. The cluster was obtained using Ward's minimum variance method (ANOVA sum of squares between both variables) to estimate the minimum distance between single linkages.

5.3. Examining Tradeoffs

A fundamental way to explore the benefits of the restoration goal for the upper Gulf is to compare the economic value of the fisheries operating in the region. The benefits estimated for each of the 76 scenarios are based on the Net Present Value.

The management policy for marine ecosystems clearly states that economic considerations are not sufficient and that future policies and restoration goals must include all sectors of the ecosystem, such as social and biodiversity components (Sumalia and Walters, 2003, 2004; Pitcher *et al.*, 2005). In this exploratory analysis, a biodiversity index Q-90 (Ainsworth and Pitcher 2004) and profits based on the Net Present Value (based on the 2000 model) were included in the simulations to compare the restoration goals for each scenario. Tradeoffs between economic values and biodiversity (measured by the Q90 index) for the 76 scenarios were considered for each of the three models of the upper Gulf of California (1950, 1980 and 2000) where the optimized fishing simulations were grouped according to their objectives (economic, social, ecological and rebuilding) on the x-axis. The profits resulting from the fishing simulations are presented on the left of the y-axis (no discount rates were included). The right side of this Figure illustrates the biodiversity of each scenario as measured by Q-90 statistics (Ainsworth and Pitcher 2004).

Before examining the tradeoff of the restoration goals employed in the region, it is worth mentioning the depletion of exploited stocks in the upper Gulf, including a loss of 6% in the biodiversity between 1950 and 1980 and approximately 8% from 1950 to 2000 (Fig. 70). In general, it was found that 'economic' and 'social' scenarios produced ecosystems with higher profits, but they tended to sacrifice diversity. Vice versa, the 50-years of simulation indicated that all the scenarios categorized as 'ecological' and 'rebuilding' resulted in ecosystems with the highest biodiversities, but with profits lower than those estimated in the 2000 model (Fig. 71). The results obtained from the 'mixed' scenarios do not display a definite pattern, but it could be said that they represent a balance between

the four criteria considered. The 'success' of future restoration goals and fishing plans must include a full evaluation in each of the social, economic and ecological fields with the participation of experts in order to increase the likelihood of developing restoration scenarios and targets with more solid and realistic backgrounds and to meet with the management regimes needed in the upper Gulf.

The exploratory analysis presented in this chapter illustrates the need to perform a more complete and detailed analysis of the cost-benefits of fishing strategies before considering any policy goal in the upper Gulf and its biosphere reserve. The social factor is considered to be one of the key elements in future plans for the management of this region because, as illustrated in section 3.2 (Chapter III), the complexity of local fishers of both industrial and small scale fleets could result in sudden protests and impediments to establishing reductions in quotas key to achieving more sustainable management for some of these sectors.

For this reason, it is recommended that educational programs be introduced among the several fishing camps along the upper Gulf with the goal of emphasizing two critical aspects. The first aspect would focus on the enormous relevance of the interaction between non-commercial species and those that have been historically exploited. This effort could result in a better appreciation of charismatic species such as vaquita, other marine mammals or turtles in the future by fishers who may expect to find a positive relationship between the biodiversity of the upper Gulf and their catches. The second factor that could be considered in these educational programs would be towards the vision and value of long-term sustainable exploitation – the food and livelihoods security concept - explaining the relevance and reasons for attempting to restore biomasses of the long lived target species such as totoaba, sharks or corvinas for the future richness and fishing of upcoming fishing generations.

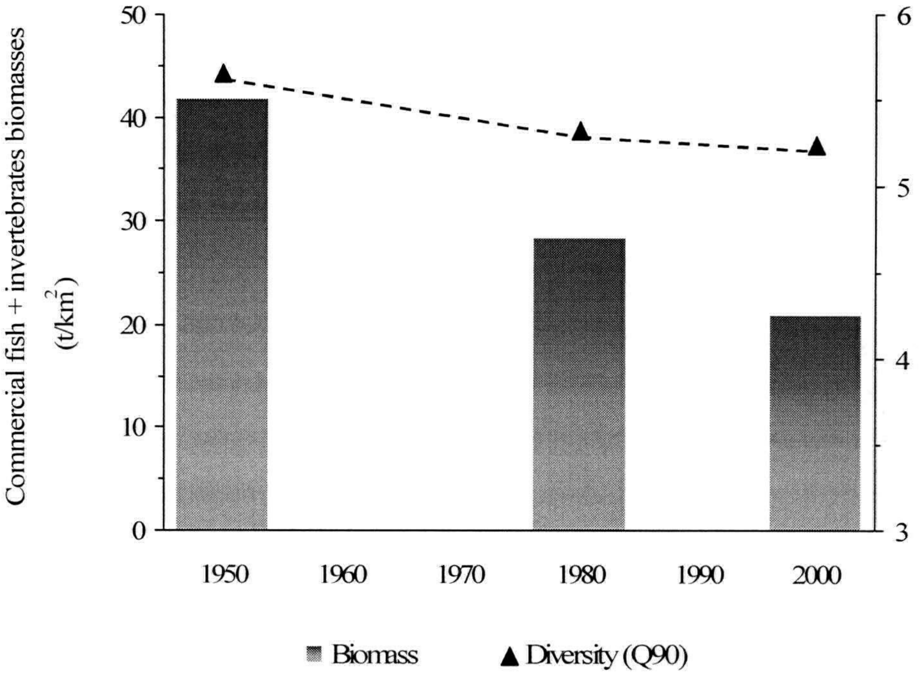

Figure 70. Depletion of stocks (fish and invertebrates) estimated in the upper Gulf of California from 1950 to 2000: taken from the three Ecopath models presented in this thesis. Broken line represents a reduction in the biodiversity of this ecosystem (estimated by Q-90 Index), with a loss of approximately 8% in the last five decades.

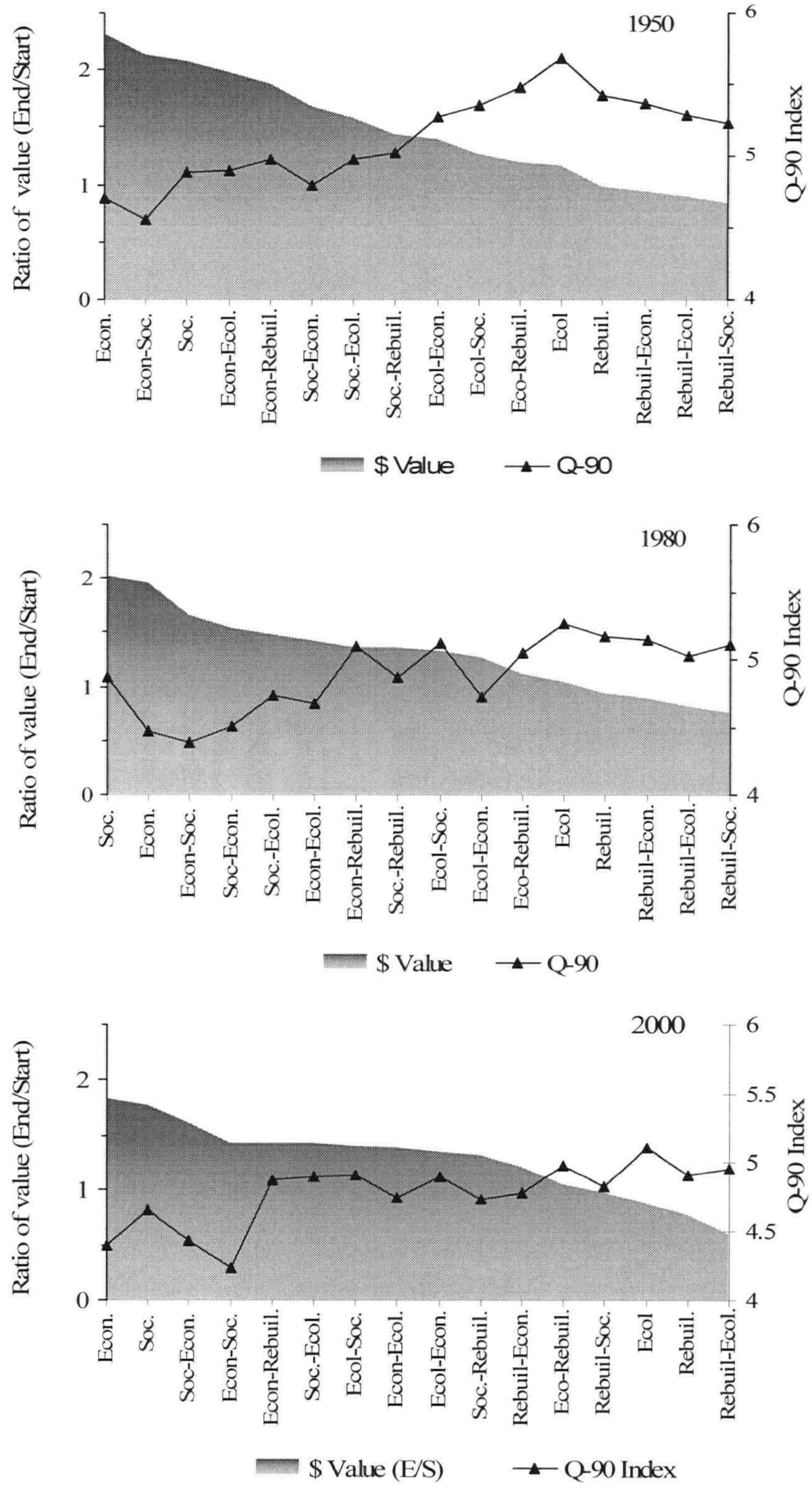

Figure 71. Tradeoffs between economic values ($US) and biodiversities estimated in the upper Gulf of California from 1950 to 2000. See text for details.

5.4. Exploring influence of climate on the food web structure and productivity of the upper Gulf of California.

One of the lessons illustrated by the last three decades of fishing is that not all changes in marine fish stocks are due to fishing pressure. Examples in practically all productive marine ecosystems have shown that for many fish stocks, climate change and long-term natural fluctuations also play an important role (i.e. Polovina *et al.,* 1994; Schwing *et al.*, 2002; Lavín *et al.*, 2003). Centuries of fossil records from periods prior to industrial fishing demonstrate long-term patterns from 400 AD to 1980 AD of low and high abundances of sardines and anchovies in the Pacific current which concur with regimens of climate change (Baumgartner and Christensen, 1985; Baumgartner *et al.*, 1993; Lozano-Montes, 1997).

The Gulf of California is strongly affected by climate fluctuations such as El Niño, which is the strongest identified cause of interannual anomalies in the region (Robles and Marinone, 1987; Marinone, 1988; Ripa and Marinone, 1989; Lavín *et al.*, 1997). Baumgartner and Christensen (1985) found that the interannual changes in the ocean climate of the Gulf of California (indicated by sea level and temperature anomalies) were explained by the ENSO cycle. Direct evidence of high surface temperatures, reduction in salinity (0.1 to 0.3) and changes in the thermocline in the Gulf of California were reported during the 1992 El Niño (Fernandez-Barajas *et al.*, 1994). Soto *et al.* (1999) also used satellite infrared images of the GoC to evaluate interannual anomalies of sea surface temperature from 1984-1995; these images showed that the most important interannual sea surface temperature (SST) anomalies relate to El Niño events. These observations were echoed by the results from 1984 to 2000 reported by Lavín *et al.* (2003), who found a statistically significant positive trend between SST and interdecadal variation of the Pacific Ocean, where the 1988-1999 La Niña produced the largest negative anomaly in SST during the period 1984-2000 (Fig. 72).

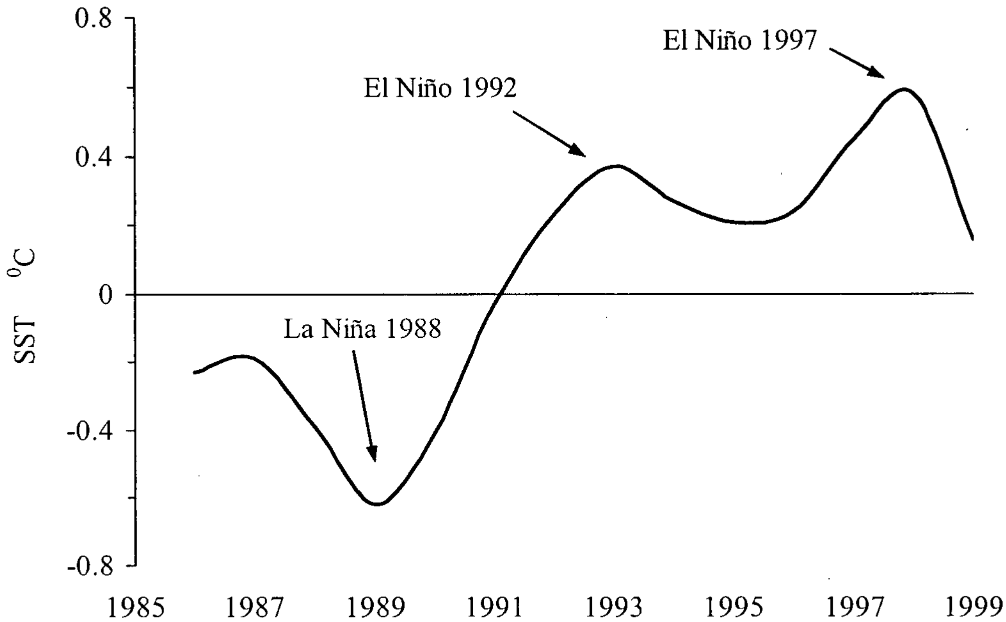

Figure 72. Time series of the monthly SST anomalies (after removing the mean, 25.47 °C) in the Gulf of California reported by Lavín *et al.* (2003). The most notable positive anomalies were explained by El Niño events in 1992 and 1997 and the largest negative anomaly was due to the 1988-1989 La Niña.

In addition to El Niño and La Niña events, there are important interdecadal changes in the rainfall reflected in the Pacific Decadal Oscillation (PDO), resulting in direct changes in the water, nutrients and sediments delivered by the Colorado River into the upper Gulf. For example, the entire Gulf of California was below normal rainfall during the 1990s decade, with a drought period that began in 1992 in the Northern region (Brito-Castillo *et al.,* 2002). Changes in the Pacific climate observed from 1998-2001 suggest that the Pacific is entering its cold phase. The current knowledge of the PDO phase is insufficient to predict which kind of period, either below or higher than normal humidity will happen in the summers of the Gulf of California (Hare and Mantua, 2000). Due to the practically zero correlation (r = 0.03) between long-term summer fluctuations of rainfall and PDO index from 1921 to 1999 in the Gulf of California (Brito *et al.,* 2002), it was decided not

to include the PDO index as a forcing function of the trophic models of the upper Gulf. Instead, the strongest anomalies in temperature and changes in precipitation due to El Niño and La Niña events were employed during this exploratory analysis as the main environmental forces interacting with the trophic models presented.

In order to explore possible effects of environmental factors on the components of the food web in the UGC ecosystem, one of the built-in routines of Ecosim (Christensen *et al.*, 2004) was used to evaluate not only the impact of physical and environmental parameters on the trophic interactions driven by primary production but also the cascade of effects on the system. This routine, which is known as 'forcing function', is generally applied directly to primary producers (Christensen *et al.*, 2004).

Figure 73 presents the forcing function I used in the simulations, in which three El Niño events (1983, 1993 and 1997) and one La Niña 1988-1989 event were considered. The forcing function was derived the scaling of the biomasses of phytoplankton obtained by local surveys and those calculated by the model through Monte Carlo runs. This scaling was incorporated into Ecosim in order to explore the effect of dams along the Colorado River on the trophic interactions driven by primary production. When applied as a forcing function on primary producers, this time series not only produced a cascade of trophic impacts on primary consumers, as was expected, but also affected top predators, such as sharks and marine mammals (including vaquita). Primary producers (mainly phytoplankton) clearly flourished as a result of the strong El Niño recorded in 1983, possibly due to the addition of nutrients brought with the floods of the Colorado River. The boost of primary production was associated with increases in the biomass of primary consumers and lower trophic levels that simultaneously provided energy to higher trophic levels. Figure 74 illustrates this cascade of energy through the whole food web as a result of the enrichment of nutrients delivered during El Niño 1983 and, on a smaller scale, in El Niño 1993 and 1997.

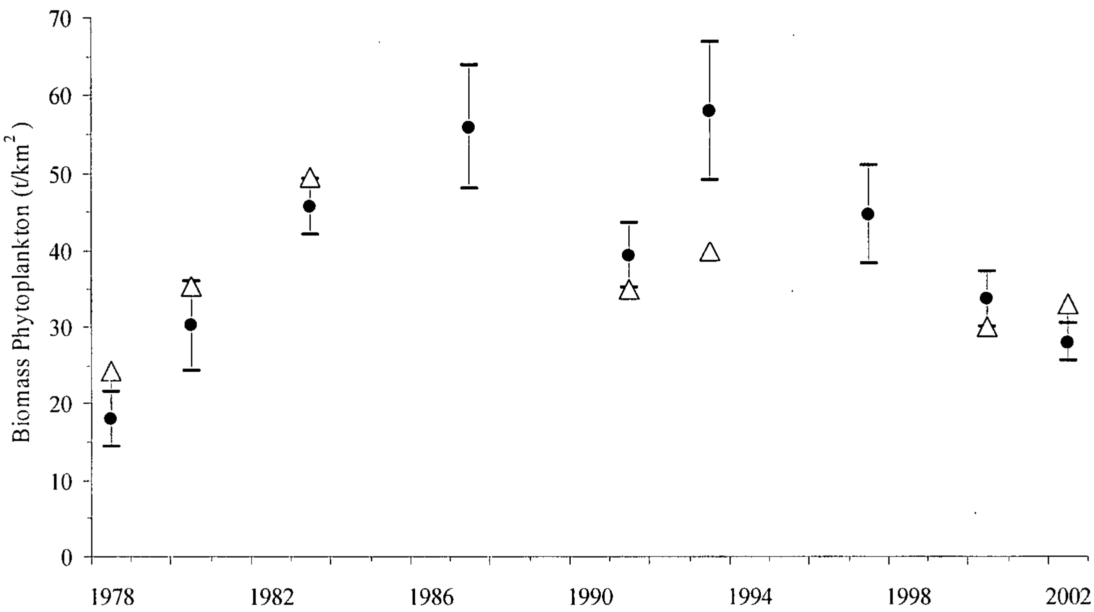

Figure 73. Time series of the biomass of phytoplankton obtained by surveys (triangles) in the upper Gulf of California from 1974 to 2002 compared with that estimated by the model (black circles). Bars represent standard deviation of the mean. This time series was used as a forcing function in Ecosim to explore the effects of dams on the trophic interactions driven by primary production (see text for details).

In some extremes cases, e.g., blue shrimps, crabs and sardines, it was found that the biomasses of these groups increased up to five times in El Niño events. This behavior echoes the elevated catches of shrimp in the upper Gulf during the Colorado River floods (Galindo-Bect and Glenn, 2000). The mechanism through which the river discharge might have affected the shrimp fishery is unknown (Galindo-Bect and Glenn, 2000); however, lower salinity may have improved the survival of early life stages by providing an expansion of the nursery areas which could have resembled past conditions of the upper Gulf as described by Sykes (1937), Osorio-Tafall (1943) and Leopold (1949). Aragón-Noriega and Calderón-Aguilera (2000) demonstrated that blue shrimp post-larvae were significantly more abundant in those years when the freshwater flow reached the upper Gulf (mainly by El Niño 1993 and 1997). It is also worth mentioning that, during the LFK analysis (Chapter III), the local fishers reported a migration of sub-adult blue

shrimp from estuaries to the marine waters during the sporadic discharges of the Colorado. They also stated that their catches are strongly influenced by the freshwater delivered by the Colorado River (more details are explained in section 3.2 of Chapter III).

Besides a significant relationship between catches and freshwater as presented by Galindo-Bect and Glenn, 2000), there is also a significant relationship between the interannual variations in the growth of the brown shrimp and the temperature in the Gulf of California, where growth of this species was favorable only when during El Niño of moderate or weak intensity, as in 1993. However, during more intense events, such as those in 1983, the effect on growth was adverse (López-Martinez *et al.*, 2003).

The results presented in Figure 74 must be taken as preliminary. i.e., cannot yet be used as a confident prediction of future changes in the abundance of stocks or population of species in the upper Gulf during El Niño events. There are several points to be considered in the modelling of the interaction between marine ecosystems and climate change. For example, it is important to realize that fish populations are not in a steady state; rather, they are affected by spatial and temporal changes in the environment and they respond to the environment in different ways. It is widely known that the biological responses to climate variability are both complex and not well understood. Indeed, life cycles and reproduction are key elements in future evaluations of global warming and climate variability.

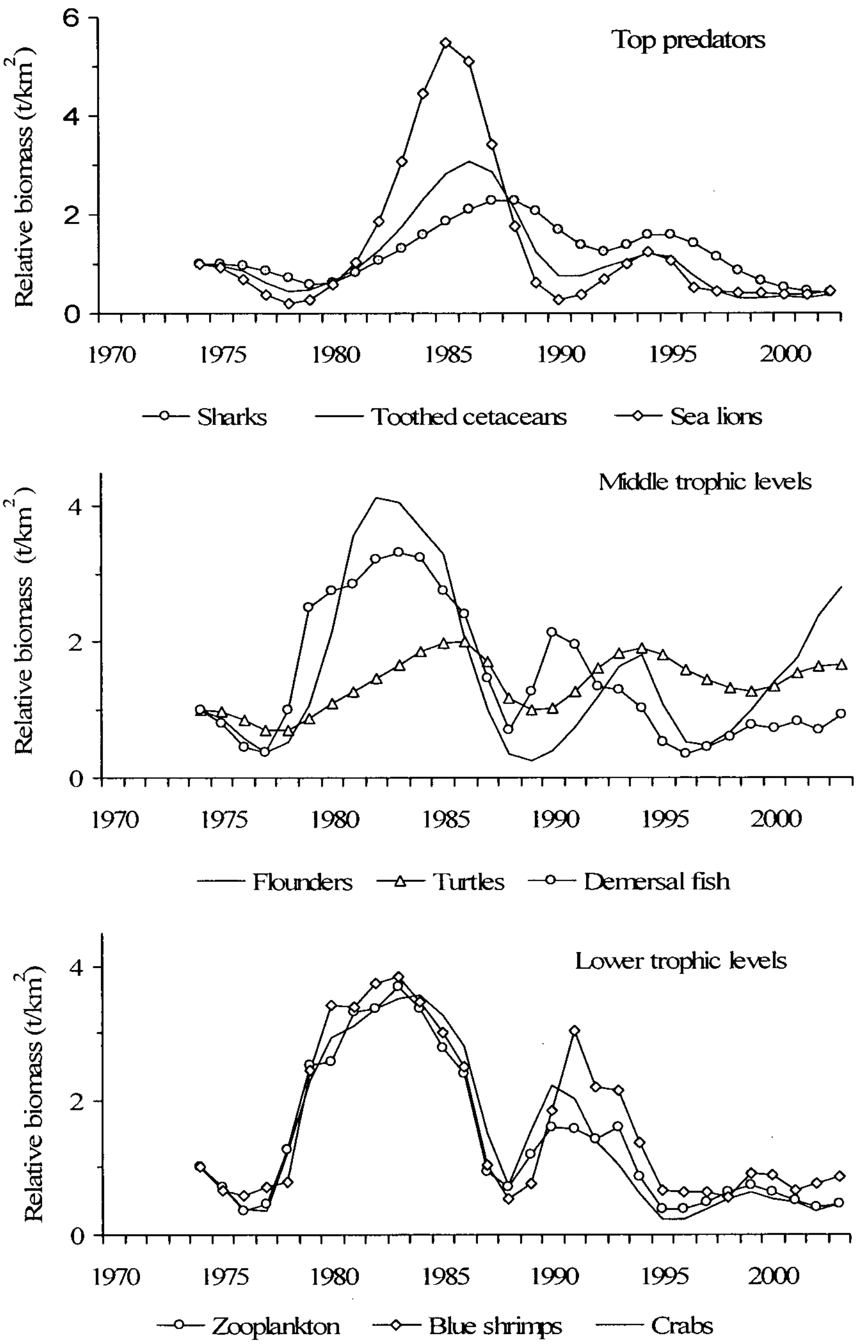

Figure 74. Simulated changes in relative biomass of nine groups of organisms from 1974 to 2002 as a result of the changes in the water and nutrients delivered during the floods of 1983, 1993 and 1997 associated with the El Niño events. The model suggests that biomasses increased across the entire food web of the upper Gulf of California.

5.5. Exploring the effect of damming of the Colorado River on the biomasses of the upper Gulf of California.

Recent research has confirmed the importance of freshwater input water on the ecology and future restoration of the upper Gulf and its delta (Glenn *et al.* 1992, 1996, 1999, 2001; Zengel *et al.*, 1995; Morrison *et al.*, 1996; Lucke *et al.*, 1999; Pitt *et al.*, 2000; Cohen *et al.*, 2001). Before upstream impoundments and diversions, the Colorado River contributed with 30,000 10^6 m^3/year, supporting tremendous biological productivity and diversity (Lucke *et al.*, 1999). More recently, flood releases have been significantly correlated to a rise in shrimp catches in the upper Gulf (Galindo-Bect *et al.*, 2000; Aragón-Noriega and Calderón-Aguilera, 2000; Aragón-Noriega and García-Juárez, 2002), indicating a relationship between the potential renewal of estuarine habitats and the amount of water delivered. It is worth mentioning that hydrographic studies have shown that the effects of the water from the Colorado River reach as far as 70 km from the river mouth (Lavín and Sánchez, 1999).

The results of section 5.3 provided evidence that regional rainfall in the upper Gulf is strongly influenced by El Niño events and PDO and that this rainfall results in increments in freshwater, sediments and nutrients delivered to the region. These inputs simulate increased primary production. Climate, rainfall and primary productivity in the upper Gulf are tightly coupled. The history of the Colorado River underscores the need to explore the phenomena associated with interruptions to freshwater inputs to coupled atmosphere and marine ecosystems.

Reconstructed discharge volumes of the Colorado River at the Southerly International Boundary based on the US Bureau of Reclamation (1952) as reported by Cohen *et al.* (2001), were used to explore the potential effects of the dams built along the Colorado River from 1950-2000. Figure 18 presents the undepleted discharge of the Colorado River that was used as forcing function affecting the primary production of the 1950 model was used as a primary production forcing function in the 1950 model (this mass-

balanced model was fitted with data originating from surveys and stock assessments as explained in Chapter IV).

The estimated undepleted discharge was incorporated into Ecosim as a forcing function throughout 50 years of simulation. No changes in fishing pressure, consumptions or diets were made during this analysis. At the end of the simulation, the final simulated biomass for each of the 50 groups was compared with that estimated from the surveys, stocks assessments and LFK analysis used to build the 1950 model (details of the biomasses and data sources are presented in Chapter III). Figure 75 shows the differences in the biomasses estimated by the model.

The major differences were found in the primary producers and consumers, such as phytoplankton and zooplankton. Significant changes were also noted in the lower trophic level groups, such as crabs and benthic fish, which are dependent on detritus food chains, Overall, the simulation results confirmed the historic role of the Colorado River as the main mechanism that provides nutrients and support richness in the upper Gulf (Sykes, 1937; Osorio-Tafall, 1943, Leopold, 1949, Alvarez-Borrego, 1999, Glenn *et al.*, 2001); an increase in the primary production of up to three times the normal amount was obtained after a 50 year scenario in which the huge dams (i.e. Glenn Canyon Dam) were removed from the 1950 model. Biomasses of higher trophic groups, such as totoaba, vaquita and sharks also increased when the system was exposed to undepleted flows of nutrients and water from the Colorado River. These results echoed the observations reported by Glenn (1998), i.e., that vaquita and totoaba may be more numerous in the estuarine region of the upper Gulf after flooding years. Vis-à-vis conservation considerations, it is important to remember that the upper Gulf (mainly Montague, Gore and Pelicano Islands) is used by at least 74 species of bird, including approximately 200,000 wintering shorebirds living in the mud lands (Mellink *et al.*, 1996, 1997). The western population of North America's white pelican population, which has been on the decline for many decades, relies on the Delta as a migratory stopover (Brusca *et al.*, 2001).

Different levels of the reconstructed undepleted flow from the Colorado River by Cohen *et al.* (2001) were used to explore a possible minimum discharge that could produce an increase in the overall productivity of the upper Gulf. Several 50-year simulations using 100%, 50%, 20% and 1% of the undepleted flow were carried out to evaluate the effects of the nutrients delivered by the Colorado River.

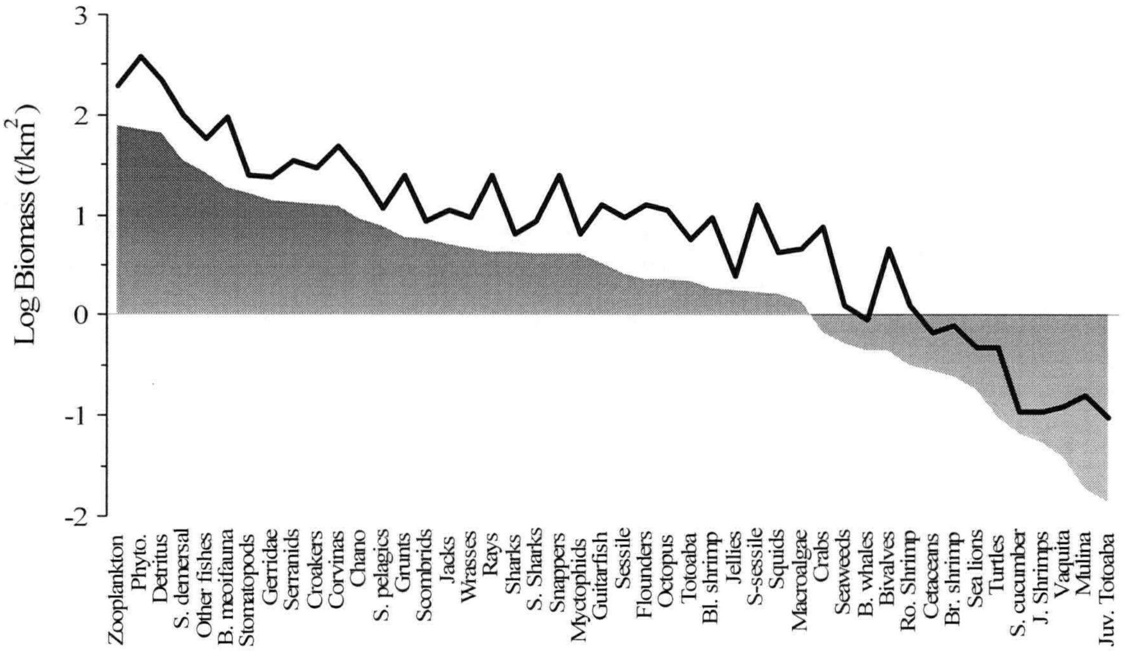

Figure 75. Biomass profiles of the upper Gulf of California ecosystem in 1950 with 50-years simulations using the undepleted Colorado River flows estimated by Cohen *et al.*, 2001 (line). This biomass, presented in the dark shaded area, is compared to the biomass of the 1950 mass-balanced model after tuning with observed data and climate factors (see details in Chapter IV). Both profiles have an equal fishing series and equal fishing pressure.

Figure 76 indicates the results from these simulations, in which the highest total biomass was found when the runoff of the Colorado River was not diverted by dams (100% undepleted), resulting in a 220% rise in the total biomass of the system. Even undepleted flows of only 1% produced increases of approximately 10% in the total biomass of the upper Gulf after 50 years, revealing the enormous role of the Colorado River in the regions' productivity. This is particularly important considering that this region provides 15% of the Mexican landings (INEGI, 2001), confirming the ecological and economical losses for Mexico during the last five decades as a result of US diversion of Colorado River.

Loss of Colorado River water has modified the hydrographic circulation in the upper Gulf (Lavín and Sánchez, 1999); furthermore, the loss in sediments has halted delta construction and exposed the entire deltaic structure to the destructive hydrodynamic forces in the sedimentary basin, promoting resuspension and erosion of sediments in the estuarine basin (Carraquiry and Sánchez, 1999). These negative forces have produced an undisputable deterioration of the upper Gulf of California with severe impact on the marine fauna including its endemic species, such as the well documented case of the totoaba and vaquita. The increase in the total biomass of the system resulting from only a 1% surplus of water from the river was an unexpected result; however, these results confirmed the observations made by Cohen *et al.* (2001), who reported that little water might be sufficient to conserve the existing riparian and wetland habitats in the upper Gulf. This observation is supported by a water balance study which suggested that even when there is no floodwater release, vegetation, including native trees and marsh plants, is supported by the scarce amount of water from the agricultural return flows (Cohen *et al.*, 2001). Even modest flood releases are sufficient to induce over bank flooding and to germinate new cohorts of native trees (Zamora-Arroyo *et al.*, 2001). An analysis of the vegetation response to past flow events estimated that 0.5% of the mean annual flow from the Colorado River could be sufficient to maintain the vegetation and wetlands of the northern region of the Colorado Delta (Cohen *et al.*, 2001).

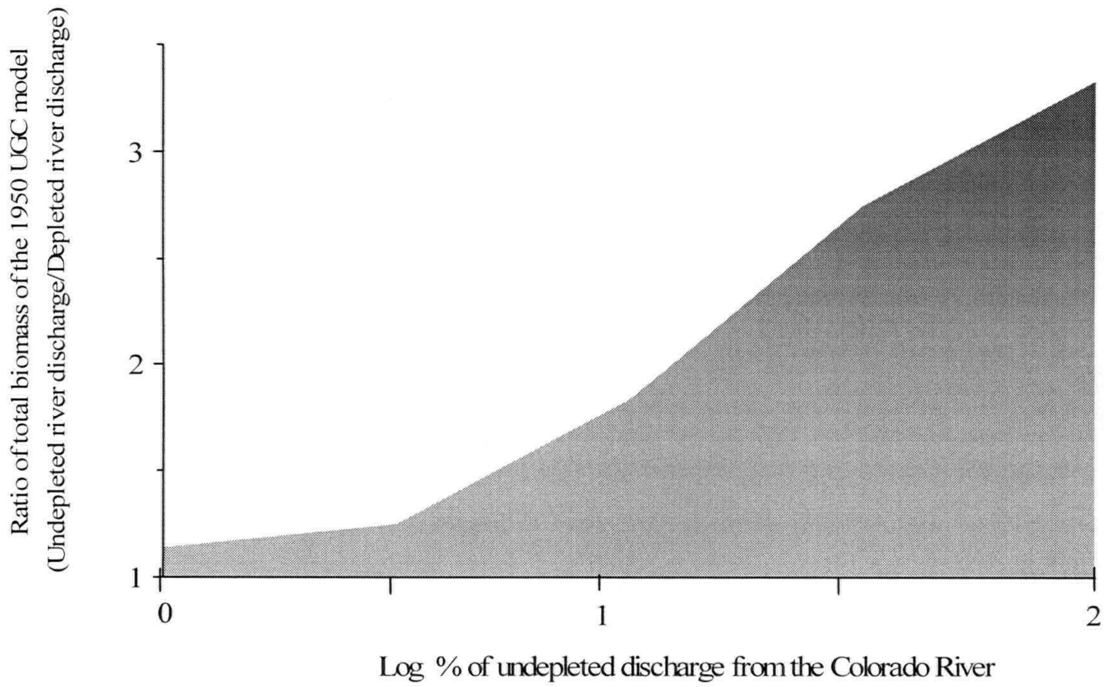

Figure 76. Changes in the total biomass of the 1950 upper Gulf of California model after 50 years of trophic simulation under different percentages of undepleted Colorado River discharge.

5.6. Conclusions.

The results presented in this section are preliminary. It is not suggested that these results provide a realistic goal for future management plans or policies in the upper Gulf of California. There are some gaps in the biological and physical fields, such as upwelling processes, seasonal modulation of the discharges, tidal mixing, water-mass formation due to salinity gradients, vertical and horizontal distribution of isohalines, sediment transport, and accumulation. All these need to be improved in the future in order to understand the relationship between water discharge from the Colorado and productivity of this system. These results illustrate not only the relevance of considering the environmental influence on marine ecosystems, but also the superficiality of our knowledge of the quantitative

process of simulation and reconstruction of past states of natural aquatic ecosystems such as the upper Gulf of California.

Any attempt to restore the upper Gulf must begin with a parallel study of the climate changes and their influences in the region. It will be crucial in the next project to establish the differences between past climate regimens with those observed during the present day because the extent of these differences will determine the potential degree of restoration. In addition to the climate influence, future restoration research will require ecological, social and economical criteria in order to choose the best restoration goal. The author of this thesis believes that results presented in this chapter could serve to guide future research with the aim of recapturing the former diversity and health states of the upper Gulf of California.

Chapter VI

Summary and Concluding Comments.

The overall objective of this thesis was to use a ecological theory to evaluate trophic changes in the upper Gulf over the past 50 years as a result of the elimination of nutrients by the series of dams built along the Colorado River and by the intense fishing pressure that has been imposed over the past several decades in this ecosystem. The 50-year trophic modelling of the upper Gulf of California faced several challenges which included having to cope with poorly-known aspects of the basic biology of key species (commercial and non-commercial species) as well as the relative paucity of research and data in the fisheries field. Better information in these fundamental areas is critical to evaluate possible changes in the system as a result of direct or indirect human presence, such as fishing or elimination of nutrients by dam construction, respectively and to develop restoration strategies that are robust to natural variability and climate and realistic and acceptable to fishers.

The following specific aims directed this thesis: to develop present and former states of the UGC ecosystems using trophic ecosystem models representative of 1950, 1980, and 2000 covering their major fluxes: phytoplankton and primary production, zooplankton and secondary production, major fish species and their fisheries, marine mammals and their food consumption. Qualitative information and knowledge from local fishers of this region (San Felipe, Baja California; Puerto Peñasco and Golfo de Santa Clara, Sonora) was also gathered as an additional tool in order to estimate relative abundances of non-commercial species during the 1950s and 1980s. Changes in the UGC ecosystem form and function were explored by comparing the models using time-changes based on dynamic simulations in Ecosim and by studying the effects of inter-annual climate variations such as El Niño/La Niña in the structure and function of the UGC. This research required a complex integration of several methodologies in the ecological, social and physical fields in order to evaluate the history of a complex marine ecosystem.

In Chapter II, I evaluated the incentives to misreport catches during the history of the fisheries of the Gulf of California in order to incorporate more realistic catches into the trophic models of the region. Discards, illegal and unreported catches in the Gulf of California are a current problem which Mexican authorities are attempting to tackle. For example, in 2002 approximately 1,200 permits were granted to boats in the Gulf of California and Pacific Ocean, and it is estimated that 20 to 30 percent of their catch was illegal (Weiner, 2002). The incentives and estimates for unreported catches reported in Chapter II require more accurate and detailed information from the dozens of fishing camps along the Gulf, especially as to how their catches are registered by local offices and how their reports are sent to the National Fisheries Institute. A direct consultation with owners and workers of vessels operating in the gulf will definitely play an important role in abating or eliminating IUU fishing. However, these estimations are open to discussion and collaboration with Mexican authorities in order to establish realistic anchor points to convert the qualitative estimations to misreport catches into values that can provide confidence intervals throughout a Monte Carlo simulation based on likely error ranges, as it was obtained to evaluate the impact of IUU fishing in other marine ecosystems (Pitcher *et al.*, 2002; Ainsworth and Pitcher 2004). The evaluation of illegal fishing in the upper Gulf of California is a fundamental aspect in the future management of this ecosystem; that is of significant cultural relevance to Mexico, provided fishing for hundreds of years to several indigenous communities and even today, produces 10% of the total marine production. Consequently, there is an obligation to estimate the true magnitude of illegal and unreported fishing in this area. It is worth mentioning that, during the last decade, the Mexican government took the initiative to combat the ecological and economic crises of the late 1980s in the Northern Gulf by implementing new regulations which included: (1) the establishment of a Biosphere Reserve in the upper section of the Gulf; (2) the creation of NOM (Mexican Official Standards) as an instrument to manage the most important fisheries and to avoid an increasing trend in fishing effort; (3) the mandatory use of turtle excluder devices; founding international committees for the recovery of the vaquita (CIRVA); and (4) a variable closed season for

shrimp by area, using the Mexican Navy to patrol areas of ecological and economic interest. While some obstacles remain, i.e., inadequate scientific resources to address many artisanal fisheries, lack of local government participation in management and the refusal by government scientists to share detailed data (Hernández and Kempton, 2004). Mexico's current fisheries policies, seem to respond to long-term problems, prevent the growth of illegal fishing documented during the 1970s and 1980s.

Chapter II incorporates total extractions (reported + illegal fishing) from the fisheries in the upper Gulf into the 2000 trophic model. This enables the model to produce more realistic results of the interaction and impact of fisheries as one of the main predators in the upper Gulf. Overall, the results of Chapter II show that the mortality imposed by fishing could be considered as the second top predator in the region, just behind the pressure imposed by large sharks. The 2000 model also confirms that fishing pressure in the UGC is dispersed throughout all trophic levels, imposing high mortalities not only on top predators but also on the bottom of the food web. For example, the large-scale industrial fleet (mainly shrimp trawlers) not only has impacts at the lower trophic levels of benthic resources, but also produces a cascade of negative effects that reach higher in the food web, mainly through the high rate of discards, thus eliminating organisms that have the potential to be consumed by higher trophic levels.

Chapter II also displays the important role of detritus (associated with nutrient loads) transported by the Colorado River, where addition of these elements to the system result in increases of biomass. This response could be explained by the 180 millions of tones per year of nutrients and organic matter that used to be delivered each year by the Colorado River, promoting the productivity of lower trophic levels (especially to those groups which are linked to the detritus flows). These, in turn provide energy for higher trophic levels, leading to higher catches. A similar response has been shown in real conditions in other marine ecosystems, where an increase of detrital biomass provoked a rapid functional response in detritivores with a subsequent positive influence on higher trophic levels (Graf, 1992). Due to the substantial relevance of detritus and nutrients in

the trophic interactions of the upper Gulf, it could be said that this system is driven not only by these elements (suggesting a bottom-up system; Carpenter *et al.*, 1985), but also the significant impact of predation by large fish (sharks, totoaba, scombrids, and serranids) also indicates the influence of 'top-down' forces (Carpenter *et al.*, 1985), indicating a more realistic 'mixed' control of the food web in the upper Gulf of California. Overall, the results obtained from the model suggest that Sykes's original description (Sykes, 1937) of the upper Gulf and its delta as an ecosystem driven by the detritus delivered by the Colorado River still holds.

The last section of Chapter II compares of the energy flows estimated for 2000 in the upper Gulf with those reported in other marine ecosystems in the Gulf of California and Gulf of Mexico. The suggestion by Morales-Zárate *et al.* (2004) that the northern section of the Gulf of California is a dynamic system at a mature stage of development is supported by the results found in Chapter II. The total system throughput (sum of all flows) suggests that the upper Gulf is a relatively small, but highly productive system. This is corroborated by observations made over decades that the upper Gulf and delta are a feeding ground and area of protection for larval and juvenile stages of many fish and vertebrates (Sykes, 1937; Alvarez-Borrego, 1975; Pérez-Mellado, 1980; Pedrín-Osuna *et al.,* 2001; Campoy-Fabela, 2002).

Several useful insights emerged from the balancing process of the 2000 model presented in Chapter II. It was possible to identify which areas or groups in the system need more research and understanding, The unbalanced 2000 model suggested that benthic communities (polychaetes, sea cucumbers, snails, scallops, oysters, clams, murex, sea stars, octopus, crabs and others) are the weakest link; more information about their biology, production and consumption is required in order to understand their interactions in the system, including their response to human activities. In future, the trophic imbalances of these eco-groups must be resolved through biological research and a better understanding of their roles in the food web rather than by solving the linear equations of Ecopath.

The second half of Chapter II presents a critical aspect for the building and modelling of marine ecosystems, the process known as tuning. It provides adjusted models (based on stock assessment data) that can track changes in biomass that are known to have occurred in the past. The fitting of the 2000 model was based on the fishing mortality obtained from time series data (1983-2000) of relative abundance (e.g., catch per unit effort CPUE) or absolute abundance estimates (e.g., survey biomasses) for each of the main groups exploited in the region. These estimates were based on several databases obtained with considerable effort by the Mexican Government; including the biomasses surveyed by the National Institute of Fisheries, and biomasses reported in the region from 1978 to 2003 (Pérez-Mellado, 1980; Magallón-Barajas, 1988; Nava-Romo, 1994; Crip-Ensenada, 1996; López *et al.*, 1997; Aragón-Noriega *et al.*, 1999).

The tuning process was also weighted by the biomasses and catches of shrimp recorded in the region. The incentive to put more emphasis on this group is because its biology and population ecology have been the subject of intense study in the upper Gulf for decades (Felix-Pico, 1975; Pérez-Mellado, 1982; Pérez-Mellado and Findley, 1985; Magallón-Barajas, 1988, CRIP-Ensenada/INP, 1996; Aragón-Noriega *et al.*, 1999; Aragón-Noriega, 2000; Aragón-Noriega and Calderón-Aguilera, 2000, 2001; Calderón-Aguilera *et al.*, 2002; Aragón and García-Juárez, 2002; SAGARPA 2003). The shrimp fishery is the most important source of income in the upper Gulf, probably representing the best-known species there, if not in the entire Sea of Cortez (50% of the Mexican shrimp production originates in the Gulf of California; García-Caudillo *et al.*, 2000). As Figure 14 indicates, a correlation between the predicted biomass of shrimps with that estimated by local surveys was obtained, resulting in a mass-balanced model that is also fitted with observed data, thus giving it some degree of validation.

In Chapter III, the elements and points to be considered for building the trophic models of the upper Gulf of California representative of the periods of 1950s and 1980s were developed. These periods were carefully selected because they include two of the main events in the history of the upper Gulf: the completion and filling of the Glenn Canyon

Dam (1961), and the intense El Niño recorded in the Gulf in 1982-83. One critical element incorporated in the modelling of the past states of this ecosystem was the LFK analysis (Local Fishers Knowledge) comprising 49 semi-structured interviews conducted with fishers of the upper Gulf (San Felipe, Golfo de Santa Clara and Puerto Peñasco). The LFK survey had two purposes: (1) to gain information about the fishers' perspectives about possible changes in the perception of past states of the UGC, including losses of abundances and diversity as a result of fishing and the effects of the Colorado River Diversion; and (2) to obtain estimations of relative past abundances of non-commercial species, a critical aspect for the building of past trophic models of the UGC. Through the LFK analysis, which was the only available source of information, it was possible to obtain estimations of past abundances of non-commercial species (i.e. vaquita, turtles, sea lions, dolphins, whales,) before the 1980s.

At the same time, LFK provides evidence that supports the observations made by Sáenz-Arroyo *et al.*, 2005, who pointed out the potential use of fishers' perceptions and historical anecdotes to quantify important declines of megafauna in the Gulf of California because, according to their research, sharks, turtles and big groupers have declined in the central Gulf of California over the past 60 years. This phenomenon known as shifting environmental baselines, represents all the inter-generational changes in the perception of the state of the environment (Pauly, 1995); however, this phenomenon has been reported not only for fisheries or environmental perception, but also in social sectors (www.shiftinglines.org), explaining why people can be so tolerant of the depletion of resources or increasing violence, respectively.

Some of the results from the LFK analysis presented in Chapter III not only revealed significant differences among the three generations of fishers with respect to the number of fishing sites depleted in the last 50 years, but also provided evidence to support a shifting of environmental baselines phenomenon in the region. The reduction of the fishing sites was explained by the fishers as the result of decades of overfishing and the elimination of nutrients from the Colorado River. In addition, significant differences

were found in the mean size of the biggest totoaba caught among the three generations of fishers, providing even more evidence of the existence of shifting ecological baselines. It was perceived through the LFK analysis that young fishers of the upper Gulf are very tolerant of the loss and collapse of their fisheries. Three major fishery crises have been documented in the region: the totoaba fishery collapse in the late 1970s, followed by the collapse of the shark fishery in the mid 1980s, and more recently, the collapse of the shrimp fishery in the early 1990s. Overall, it was perceived that young fishers have the impression that old fishers always exaggerate the richness and diversity of the upper Gulf in past decades and that the old fishers are not correct when they state that the upper Gulf once supported colossal populations of totoaba, sharks, Pacific sierras and other predators (suggesting equal richness in the abundances of their preys). Such a rapid shift in the perspective of the degradation of the environment (in just a few decades) is a very important red flag to be considered by both the Mexican government and management authorities if they wish to promote conservation of the region through courses, seminars or any other educational tools in order to raise the ecological and economic value of the upper Gulf of California.

Another red flag raised by the LFK (besides the elimination of nutrients delivered by the Colorado River) was the pollution of this area by agricultural runoff and the recent drug traffic. A recent report confirmed the mortalities of 367 dolphins, 51 sea lions, 8 whales and more than 200 seabirds in San Felipe (Baja California) were caused by consuming NK19, a synthetic cyanide compound used for tracking illegal drugs at night (Azuela de la Cueva *et al.*, 1995). From the fishers' perspective, the future of the upper Gulf of California will rely heavily on tourism.

The second half of Chapter III presents all the interdisciplinary sources of information used to build the 1980s and 1950s models, including scientific expeditions and fish collections by Mexican and US organizations, fossils records, LFK, and dozens of scientific reports. This extensive source material was used to calculate the hundreds of parameters considered in the trophic modelling. Both past models were balanced and their

uncertainties were presented and discussed in section 3.4.1. It is worth mentioning that, before balancing the 1950 and 1980 models, there were areas and groups (benthic fish and invertebrates) in the models that were immediately out of balance, indicating that the biology of these groups in the upper Gulf is not very well understood, raising a flag for more intense research. The trophic imbalances of these groups should be resolved in future models by improving the understanding of their biology rather than by solving linear equations of the model.

Chapter III also presents another element, i.e., the *pedigree index* (P) routine in Ecopath that assists in the sensitivity analysis. This index, which ranges from 0 where data are drawn from outside the system to 1 for data from local surveys and stock assessment, categorizes the origin of the sources of information used to build the model, measuring the uncertainty associated with the type of data for each of the five basic parameters of the model (Biomass, P/B, Q/B, diet composition and catches). The overall P index of the 211 categories measured in the 1980s model 0.59 and 0.47 for the 1950s, indicates a higher uncertainty associated with the biomass estimations from the LFK analysis incorporated into the model. Finally, this chapter discussed critical points to be considered in the reconstruction of past models, such as catchability which was considered constant over the 50-years of modelling, and because of this, no changes to fishing mortality were included. Predation mortality was also considered to be constant in the linkage among the Ecopath models.

The objective of Chapter IV was to connect the 1950s and 1980s models with the 2000 present-day condition model. This connection was made through dynamic Ecosim simulations using biomasses estimated from direct surveys or stock assessment data in order to adjust the ecosystem models to reflect changes that have been observed and documented. Two additional problems needed to be overcome before connecting the three models. First, there was no reliable diet information or bycatch estimates from the 1950s. Both Ecopath and Ecosim simulations are highly sensitive to the initial diet matrix, as it determines the base predation mortality rates and the rates of effective search

for prey by predators. A second relevant aspect to be considered is bycatch (including discards and IUU) because this parameter determines the initial fishing mortality rates, which are then adjusted annually in Ecosim according to the tuning method described above. The best approach to dealing with these issues was to use the 2000 Ecopath model's initial state including its diet matrix (with the best scientific information available) as a first guess for the 1950s diets and reconstruct the (implied) 1950s trophic state. The main benefit of this approach is that (unknown) diet composition and biomasses for the 1950s model remain consistent with those implied by the 2000s model.

The tuning process presented in Chapter IV involved a wide range of sources of information, from the LFK and stock assessments (including illegal and unreported catches estimated in Chapter II) to local surveys conducted by the Mexican government since the early 1970s. During this tuning process, a statistical measure of goodness of fit of the time series data employed was generated each time Ecosim was run. Goodness of fit is represented by a weighted sum of squared deviations (SS) of log biomasses from log predicted biomasses. Using this criterion, it was possible to search for vulnerability (Vs) estimations that gave the best 'fits' of Ecosim to the time series of biomass and catch incorporated into the fitting; and then select the best overall model fitted (lower SS generated). In order to improve the fitted model (1950-2000), the interaction between the ocean and the atmosphere, a relevant aspect in the modelling of marine ecosystems, was incorporated. Natural variability (ENSO) was also considered in the trophic models as changes in the environment can be manifested by a shift in productivity, abundance and distribution of many species (Polovina *et al.*, 1994; Francis and Hare 1994, Hayward, 1997; Pitcher *et al.*, 2005).

The complex interactions between biology and climate in the upper Gulf were simulated by running the fitted model was run under the climate influence of the 1950-2000 time-series of the Colorado River discharge below the Hoover Dam, which included several overflows associated with El Niño events: 1957, 1982, 1993, 1997 (Lavín, 1999 and Lavín *et al.*, 2003). The effect of the changes in water, sediments and nutrients delivered

by the Colorado River from 1950-2000 was incorporated into the fitted model affecting only primary production. Overall, the incorporation of the environmental factors resulted in an 18% improvement of the fitted model.

The improved fitted model (that includes the climate series) was used for the dynamic simulations and quantification of the water diversion impact on the upper Gulf of California presented in Chapter V. It is worth mentioning that the vulnerabilities resulting from the tuning and climate incorporation of the 1950-2000 model displayed a realistic response to changes in fishing, in which the AVP (average predator vulnerability) displayed a significant ($P<0.05$) linear relationship with the trophic level estimated by Ecosim. This pattern is in agreement with the assumption that large predators have a broader spectrum of diet, and thus require a longer time to search for food, increasing their vulnerability to predation and mortality imposed by fishing (T. Pitcher, 2006 pers. comm.). This pattern also suggested that a decline in the biomass of potential prey resulted in the need for predators to spend more time searching for food and thus create a greater vulnerability to be caught by other predators or by fishing gear. The increased vulnerability of predators resulting from a decline in their prey is in agreement with the surveys conducted by Felix-Pico (1975); Pérez-Mellado (1980); Pérez-Mellado and Findley (1985); CRIP-Ensenada (1995), indicating a realistic decline of the benthic fauna in the upper Gulf. This trend of high Vs associated with large predators has been found in other ecosystem models in British Columbia (C. Ainsworth, 2006 pers. comm.), but with less intensity in Hong Kong models (W. Cheung, 2006 pers. comm.), thus indicating the need to explore and quantify this assumption in the future, using different trophic models of other marine ecosystems.

Generating a scale from 'healthy' to 'unhealthy' attributes for the entire UGC by quantifying the possible ecological impact of diverted waters resulting from a series of dams along the Colorado River on the upper Gulf of California was one of the main objectives and motivations of this thesis project. The effect of the water diversion from the Colorado River was based on the quantification of energy flows of the past models of

the upper Gulf, and it was compared to the flows estimated for the current state of the system (2000 model). The quantification of the energy flows provide a form and structure of the system, two key characteristics for understanding the complexity, and simultaneously, a way to quantify changes through time in the upper Gulf of California. By analyzing the flows over the 50-years of modelling, it was possible to track changes in the food web through changes in trophic levels, depletions of biomasses and changes in predation and fishing mortalities. Network analyses and emergent properties obtained from the past and present models represent just one of the many approaches that are used worldwide to define the structure and function of ecosystems. The combination of these methods represents an important step in the further comprehension of marine ecosystems like the upper Gulf of California through time and space. The connection between network analyses and changes in the biomasses estimated by Ecopath suggests that the 'Back to the Future' strategy (Pitcher and Pauly, 1998; Pitcher, 2001, Pitcher *et al.* 2005) could be useful for a comprehensive understanding of the ecosystem dynamics in the evaluation of both human activities such as overfishing and activities that threaten diversity.

The ecosystem approach used in the modelling of the UGC for the past 50 years determined the positive role of detritus in the system for all consumer organisms and for fisheries. This response could be explained by the Colorado River delivering at least 180 millions of tonnes of nutrients and organic matter every year, key factors for promoting the productivity of lower trophic levels (especially to those groups which are linked to the detritus flows), which in turn leads to higher catches. A similar response has been reported in other marine ecosystems, in which an increase of detrital biomass provoked a rapid functional response in detritivores with a subsequent positive influence on higher trophic levels (Graf, 1992). However, the loss in energy storage contained in the hundreds of millions of tonnes of nutrients and organic matter historically deposited every year by the Colorado River, but which ceased with the Hoover and Glen Canyon Dams at the end of the 1960s, supports the hypothesis made by van Andel (1964) and Cupul (1994) that the upper gulf is suffering an erosional and starvation phase because the sediments and

nutrients that were deposited during the pre-dam period have been exported and consumed at similar rates to those before the 1940s. Also, the loss of overhead in an ecosystem has been interpreted as a measure of the potential energy in reserve (Arreguín-Sánchez and Valerio, 1996; Morales-Zárate *et al.*, 2004), suggesting that the current state of the upper Gulf of California has less potential for growth and is more subject to 'perturbation' than in the 1980s and 1950s. Overall, the results obtained from the models suggest that Sykes's original description (Sykes, 1937) of the upper Gulf and its delta as an ecosystem driven by the detritus delivery by the Colorado River still holds.

The results from the network analysis from 1950-2000 revealed that the detritus group (which also includes nutrients and sediments) produced a positive cascade of effects from the bottom of the trophic structure. These results agree with the high productivities reported during decades in the upper Gulf (Zeitzchel, 1969; Álvarez-Borrego *et al.*, 1975; Álvarez-Borrego *et al.*, 1983; Brinton *et al.*, 1986; Valdéz-Holguín and Lara-Lara. 1987; Millán-Núñez, E. 1992; Millán-Núñez *et al.* 1999; García-Pámanes and Lara-Lara, 2001). The high fertility of these waters has been explained by the interaction between high nutrient levels (historically delivered by the Colorado River). Tidal currents, wind, and the plateaus' topography (Lavín *et al.*, 1999), result in numerous areas of upwelling mainly along the eastern coast of Baja California, (Argote *et al.*, 1998) which seems to have the potential to maintain large food chains with no freshwater input (Millán-Núñez *et al.* 1999), this is likely because of residual sediment from pre-dam periods, but is now a finite resource. Perhaps the reason why the sediment load from the Colorado River is almost zero today (Carraquiry and Sánchez, 1999) is because strong tidal waves (up to 12m from the mouth) removed the previously deposited sediments (before the completion of the huge dams), suggesting an erosional phase in the upper Gulf that is increased by an exportation of sediments to the Northern Gulf at rates similar to those of the unaltered river flow prior to 1935 (van Andel, 1964; Cupul, 1994), and thus creating a starvation phase of nutrients and sediments in the delta as a result of the construction of the dams.

Chapter V explored the influence of climate, ocean change and fishing on the marine ecosystem of the UGC. Understanding the effects of these three factors on the upper Gulf may allow for greater accuracy in predicting their ecological and economic impacts and for simultaneously developing stronger policies that are more robust vis-à-vis climate and ocean change interactions. The study of several ecosystems and the effects caused by changes in fishing efforts and diversity (measured by the Q-90 index) under different policy objectives (76 scenarios under consideration) was undertaken in the research presented in this chapter. It is remarkable that, at the end of the 50-year period of simulation, only seven out of the 76 scenarios produced biodiversities as well as theoretical harvests and commercial values higher than those of the 2000 model. The majority of these scenarios were considered unrealistic because they implied total or drastic reductions to current fishing efforts in the upper Gulf. Only a few scenarios resulted in diversities higher than those of 2000. Although the overall results of this exploratory analysis suggest that fishing and conservation could be compatible, the low number of scenarios with this 'win-win' characteristic suggests a substantially high risk for endangered vaquita and totoaba. The current management policies of the Mexican government in the upper Gulf focus highly on conservation and controlling the size of the fishing effort. These efforts are in conjunction with the win-win scenarios criteria for a long-term sustainable fishing in the region. The second part of Chapter V takes environmental influences into account (Colorado River discharge as a forcing factor) in the search for optimal fishing and a detailed analysis of environmental uncertainties in the 2000 model of the upper Gulf of California is also discussed.

The second part of Chapter V presents an exploratory analysis of possible effects of environmental factors on the components of the food web in the UGC ecosystem. This approach included a time-series of the water delivered by the Colorado River, where the interannual changes in the flows are explained by the El Niño events of 1983, 1993 and 1997. The results obtained showed a direct increase in the primary production in the region as a result of nutrients being delivered during the floods. The richness in primary production also produced increases of up to five times the original biomasses in most of

the species considered in the model, from primary consumers to top predators such as sharks and marine mammals. However, these results were considered preliminary and there was no suggestion that they could be used in the future prediction of environmental effects or global warming due to the substantial uncertainty of the data and the complex and poor understanding of the interactions between ocean, climate and marine populations.

During the application and integration of all the methods used in the reconstruction of the history of the upper Gulf, several assumptions and limitations of these methods were discussed in the relevant chapters, emphasizing the need to examine the impact of these assumptions in the future. This represents one of the rationales of this research, i.e., to address the deficiencies and weaknesses of the required parameters which could be examined in greater depth and whose unbalanced values could be resolved once a better knowledge of their biology is available.

6.1. Recommendations.

When quantifying human impact on marine ecosystems through analyses of trophic models, it is vital to estimate realistic extractions realized by fishing rather than simply using official statistics provided by governments. It has been demonstrated that important differences could occur between catches reported and catches obtained (Pitcher *et al.*, 2002; Ainsworth and Pitcher 2005). In the specific case of the upper Gulf of California, the incentives and estimates for unreported catches presented in this thesis require more accurate and detailed information from the dozens of fishing camps along the Gulf, especially as to how their catches are registered by local offices and how their reports are sent to the National Fisheries Institute. A direct consultation with owners and workers of vessels operating in the gulf will definitely play an important role in abating or eliminating IUU fishing. However, these estimations are open to discussion and to collaboration with Mexican authorities. Anchor points are needed in order to convert the qualitative estimations to misreport the catches into values that can provide confidence

intervals throughout a Monte Carlo simulation based on likely error ranges. These anchor points have been used as key elements to evaluate the impact of IUU fishing on other marine ecosystems (Pitcher *et al.*, 2002; Ainsworth and Pitcher 2005). In the next stage, this IUU project must include this information in order to quantify the impact of IUU fishing and obtain a better approximation of the total extractions in the Gulf of California. A quantitative estimation of IUU fishing activities represents just one of a series of effective measures to combat this problem both in the Gulf of California and worldwide. After all, the Gulf of California is recognized not only because of its cultural relevance to Mexico, providing fishing to several indigenous communities for hundreds of years, but also because its richness produces 40% of the total marine production; consequently, there is an obligation to estimate the true magnitude of illegal and unreported fishing.

As mentioned, for many groups empirical data are either sparse or non-existent, resulting in the use of diets reported in other models for the same region, but numerous shortcomings were noted. For this reason, an extensive and intensive stomach sampling program in the upper Gulf would provide more accurate estimates of the trophic interaction and quantities consumed by the key species, reducing the uncertainty associated with the role that diets played in the outputs of the Ecopath models. The second area of the model that could be improved with more accurate data is the biomass estimation; the biomasses used for many groups are poorly estimated, especially at lower trophic levels. The parameters employed in the model should be constantly revised or replaced with new estimates. Finally, seasonal variations in energy flows and system attributes were not addressed in the network analysis presented in this thesis. The upper Gulf of California is subjected to a seasonal variation in both biotic and biotic factors (Álvarez-Borrego, 1975; Alvarez-Borrego and Schwartzlose, 1979; Alvarez-Borrego, 1999; Lavín, 1999; Brusca *et al.*, 2001; Lavín *et al.*, 2003), and such variations could influence the energy flows and attributes of the upper Gulf, making this another reason for further investigation in the area.

The balancing process of the 2000 model confirmed that empirical data for many groups are sparse or non-existent, thus resulting in the use of diets reported in other models for the same region; however, numerous shortcomings were noted from those models. Weaknesses in the diet matrixes used to build the present and past models have been noted in many sections of this research. Additional comments – input from workshop with scientists, fishers and Cocapás- are warranted regarding small juvenile fish (i.e., totoaba) in the diets of predators. The three trophic models presented in this thesis provide estimates of the contribution by various predators or groups of predators; however, it must be clear that the diet information for many of these predators is not completely accurate and more research on consumption is recommended. The importance of cannibalism in large predators such as sharks needs to be calculated more carefully.

The second area of the trophic models presented in this research that could be improved with more accurate data is the biomass estimation; the biomasses used for many groups are poorly estimated, especially at lower trophic levels. This is a key element in the construction of trophic models because biomass estimates serve to scale these models. Biomass estimates are poor for many groups. This is especially true for lower trophic groups, but they also occur at higher level groups such as sharks, whales, sea lions and dolphins. The past and present models would be more reliable if more confidence could be placed in the biomass estimates. The parameters used in the model should be constantly revised or replaced with new estimates. It is important to mention that the process required to build these trophic models is essentially open-ended. The data available for inputs must be constantly added or revised. The models presented here should be considered a first step, and there is an open invitation to critique the structure, the input data and the assumptions in order to improve the models during subsequent exercises. The data presented in this model are available from the author upon request.

It is worth pointing out that the 50 years' modelling of the upper Gulf presented in this research does not include the recreational fishing sector whose impact on the region must be studied carefully in the future. This further research will provide information to

support the general consensus (according to the LFK analysis) that sports fishers produce large amounts of discards and do not record the number of fish that they catch. It will be necessary to get information from the Tourism Secretariat and from the several sport fish companies in Puerto Peñasco (Sonora) and San Felipe (Baja California) in order to estimate the number of trips and fish caught by sport fishers. In addition, seasonal variations in energy flows and system attributes were not addressed in the network analysis presented in this thesis. The upper Gulf of California is subject to seasonal variation in both biotic and biotic factors (Alvarez-Borrego, 1975; Alvarez-Borrego and Schwartzlose, 1979; Alvarez-Borrego, 1999; Lavín, 1999; Brusca *et al.*, 2001; Lavín *et al.*, 2003), and such variations could influence the energy flows and attributes of the upper Gulf. The next phase of this research must be aimed at refining the temporal and spatial resolutions of the past and present models. Temporally, the emphasis will be placed on understanding the relative role that fisheries and environments have played on the ecosystem of the upper Gulf in the last decade. Spatially, the emphasis will be on developing a version of the ecosystem model which considers the diversity of habitats in the region, such as the Colorado Delta, mud areas, and the wetlands of the upper Gulf.

Another important recommendation exposed by this research refers to the role and impact of fishing imposed by both large and small scale fleets. It was evident that large-scale industrial fleets (mainly shrimp trawlers) not only have an impact on the lower trophic levels of benthic resources, but that they also produce a cascade of negative effects that can reach the higher levels of the food web; this was explained by the high rate of discards that eliminates organisms that can potentially be consumed by higher trophic levels. In contrast, the diverse small-scale sector was more selective than offshore trawlers, with practically no discards. However, the small scale sector is fishing at practically all trophic levels. It is important to consider this impact because the Mexican government recently reduced the shrimp trawler effort in the upper Gulf, and trawling has been banned in the core zone of the biosphere reserve since the mid 1990s. However, these regulations do not seem to be sufficient because the small-scale sector also creates an impact. All sectors of the fishery must be assessed and managed, and it is not

completely accurate to label shrimp trawlers as a 'bad fishery' and the small-scale sector as a 'good fishery'.

Important recommendations could be drawn from the information received during the Local Fishers Knowledge interviews. The opinion of the fishers of the upper Gulf interviewed suggested the existence of a shifting of ecological baselines in the upper Gulf. Furthermore, young fishers indicated that they are very tolerant of the loss and collapse of their fisheries, referring to the three major crises in the region when totoaba (late 1970s), sharks (mid 1980s) and shrimps (early 1990s) were depleted to levels that resulted in the collapse of their fisheries. In a general sense, young fishers have the perception that old fishers always exaggerate the richness and diversity of the region, and that it is not true that the upper Gulf once supported the colossal populations of totoaba, sharks, Pacific sierras and other predators (suggesting equal richness in the abundances of their prey). Such a rapid shift in the perspective of the degradation of the environment (just a few decades) is a very important red flag to be considered by the Mexican government and management authorities if they wish to promote conservation of the region through courses, seminars or any other educational tools in order to raise the ecological and economic value of the upper Gulf of California. For example, it is necessary to promote the conservation of vaquita emphasizing its colossal ecological value as an endemic species. This is because many fishers have the impression that their fisheries (shrimp trawlers and shrimp gillnets) have been closed or limited due to vaquita, and they believe that this marine mammal is just a myth in the upper gulf and that the biosphere reserve is just a government hoax in order to make money for its own benefit.

Important suggestions could be drawn from the LFK analysis. It confirmed that the artisanal fisheries in the upper Gulf are complex and highly diverse. Each community has its own seasons, regions and fishing methods. Changes in tides, changes in the length of daylight and moon cycles play a role in the fishing activities of this region. Also, non-natural factors such as fuel prices, equipment costs, and market prices affect their fishing. All these variables that occur simultaneously must be considered for future management

plans in the upper Gulf of California. Also, the LFK revealed an intense desire on the part of the fishers to participate in and to be informed of all the decisions and management plans for the upper Gulf, including the Biosphere Reserve.

The biomass and trophic interactions presented in this research were also used as an initial analysis to evaluate both the diversity and economic richness of the upper Gulf, and their possible worth today if the dams had not been constructed. This ecosystem-based evaluation (considering economic, social ecological aspects) aimed at providing information that could be used for future management plans. However, the analysis showed that most of the scenarios considered were not feasible since they suggested unreasonable changes in the activities of some fleets, and such outcomes were considered unviable. The restoration of species such as vaquita and totoaba were just a few of the dozens of scenarios run and which produced reasonable reductions in fishing. Overall, it could be said that fishing and conservation could be compatible in the upper Gulf, but the low number of scenarios that achieved the conservation goals indicated a substantial risk not just for endangered species, such as vaquita and totoaba, but also for heavily exploited groups such as shrimps and sharks. After an exhaustive search, the overall results suggest that it is necessary to examine the tradeoffs presented among the win-win scenarios in more detail in order to obtain more realistic solutions.

In the case of the exploratory analysis of the climate influence on the food web of the upper Gulf of California, the results obtained must be taken as preliminary, and they are far from being used as a confident prediction of future changes in the abundance of the stocks or in the population of species in the upper Gulf during following El Niño events. There are some considerations that were raised during this analysis: it is important to consider that fish populations are not in a steady state because they are affected by spatial and temporal changes in the environment, and furthermore, fish populations respond to the environment in different ways. It is recommended that future biological research focus on life cycles and that reproduction be carried out in the upper Gulf in order to more accurately evaluate global warming and future El Niño and La Niña events. This

knowledge could be used as a first attempt to forecast similar responses of commercial fish populations, as well as their food and predators. Climate and fish management is a complex interaction, and in the future, it will be necessary to devise quotas and spatial management schemes in order to respond more rapidly to early warnings and more effectively to worse risks. Finally, it could be useful to ensure that all stakeholders and coastal communities in the Gulf of California are aware of risks and agree with contingency plans in order to avoid future fishery collapses and economic crashes not just in the upper Gulf, but also for the entire Gulf of California. A cooperative international agreement assuring sufficient quantities (10-15%) of water, delivered at the right time, will be needed in order to conserve the delta and improve the current productivity of the marine ecosystem of the upper Gulf of California ecosystems for future generations.

Some of the results presented in Chapter V (section 5.3) provided evidence that regional rainfall in the upper Gulf is strongly influenced by El Niño events and PDO and that this rainfall results in increments in freshwater, sediments and nutrients delivered to the region. These waters are subsequently enriched by a growth in primary production. The relationship between climate, rainfall and primary productivity in the upper Gulf is very close and the history of the Colorado River has confirmed the effects of climate change on the delivery of nutrients and fresh water, emphasizing the need to explore the climatic phenomenon coupled with the atmosphere and marine ecosystems.

Also, results from the simulations presented in Chapter V, in which the highest total biomass was found when the runoff of the Colorado River was not diverted by dams (100% undepleted), resulting in a 220% rise in the total biomass of the system. Even undepleted flows of only 1% produced increases of approximately 10% in the total biomass of the upper Gulf after 50 years, revealing the enormous role of the Colorado River in the regions' productivity. This is particularly important considering that this region provides 15% of the Mexican landings (INEGI, 2001), confirming the ecological and economical losses for Mexico during the last five decades as a result of the damming of the Colorado River by US dams. Vis-à-vis conservation considerations, it is important

to remember that the upper Gulf (mainly Montague, Gore and Pelicano Islands) is used by at least 74 species of birds, including approximately 200,000 wintering shorebirds that depend on the mudflats and wetlands (Mellink *et al.*, 1996, 1997). The western population of North America's white pelican population, which has been on the decline for many decades, relies on the Delta as a migratory stopover (Brusca *et al.*, 2001).

6.2. Conclusions.

The aim of the present research was to identify and analyze trophic changes in the upper Gulf of California resulting from water diverted by the series of dams along the Colorado River and by fishing over the last 50 years; however, we cannot begin to understand the ecosystem effects of fishing or of any other human impact until we understand the nature and history of interactions among the species or groups at all levels of the food web and the dynamics of the region.

The three Ecopath models provide a summary of our current knowledge of the biomass, consumption, production, food web and tropic flows in the upper Gulf of California ecosystem occurring over the past 50 years.

An examination of overall evidence resulting from the construction of the three trophic models of the upper Gulf of California relating to the past and present confirmed some of our knowledge, such as the important role played by sediments and nutrients delivered by the Colorado River in the structure and function of this ecosystem.

The analysis undertaken showed a clearer picture of the great complexity of this ecosystem: The relevance of the lower trophic groups that were directly affected by the depletion of nutrients associated with the sediments of the Colorado River; which in turn resulted in a cascade of negative effects on the trophic web, affecting both overall productivity and fishing in the region. For example, 43 out of the 50 groups included in the models showed at least a 20% of reduction in their biomass after a simulated

reduction of detritus over a period of 20-years. This is particularly important because understanding the process and interactions within the system can aid in both the future formation of long-term management policies and the restoration of the region.

The chapters presented here are examples of approaches to characterizing the responses of a whole community which has changed as a result of human efforts, and they represent preliminary steps towards developing sustainable strategies for the restoration of the region. One of the goals achieved during this research was to produce models of the past state of the upper Gulf which were generated from the present, taking into consideration the former series of fisheries and climate influence both before and after the construction of the Glenn Canyon Dam in the early 1960s. During this process, a wide variety of multidisciplinary sources of information and methodologies was amalgamated with the trophic models in order to reconstruct for the first time the history of this rich marine ecosystem. Perhaps the past models were subject to some uncertainty due to climate influence, which played a critical role in the reconstruction of the upper Gulf. The past models were adjusted using a time series of climate data, incorporating the effect of several El Niño events (1957, 183, 1993 and 1997) in the primary production estimated in the region. Some of the results presented in this research could be used as Ecosystem Reference Points (ERP), which could help in future management purposes in the same way as Biological Reference Points (BRP) proposed by Hilborn and Walters (1992) for fish stock assessments. For example, the evidence of loss in biomass and number of high trophic levels during the 50-years of modelling which suggests a 'Fishing down in the food web' phenomenon could be viewed as a symptom of ecosystem deterioration by overfishing. During the last five decades, the information provided by the trophic levels indicated important impacts by fishing, resulting in an average decline rate in the trophic levels of 0.02 TL·per decade. Also, a notable loss in the abundance of detritivores during the last 50 years was observed; it was estimated that a 64% reduction in the total biomass of all the groups located in trophic level 2 and 2.5 took place. This loss is affecting the incorporation of organic matter to higher trophic levels of the food web which is a critical function of any ecosystem. Overall, the numerous changes in the energy flows and

production rates which were estimated during the research indicated an imminent loss in the energy and dynamics of the upper Gulf. These changes affect the structure and function of this ecosystem, limiting its ability in the future to recover to its natural state. This research proved that human intervention can trigger rapid and significant changes in the structure and function of small marine ecosystems such as the upper Gulf of California.

Based on the results illustrated by this research, it is possible to visualize the future of the upper Gulf of California. Basically, there are two possible paths that the fisheries in the upper Gulf may take in the next decades. One is to continue with the same trend observed during the last five decades, in which intense harvesting and fishing pressure on all levels of the food chain will remain high, and industrial and small scale fleets will continue to catch the maximum allowed by the system in a short term. This would result in a sequential depletion of the resources, and the fisheries would then move lower down in the food web of the upper Gulf. It is predicted that fish and invertebrates species that are currently discarded or have no commercial value would thus dominate the composition of the catch and future markets of the upper Gulf. Alternatively, the research conducted in this thesis confirms the need to integrate ecological elements such as the construction of dams or reductions in fishing pressure into future changes in the region. In the future, the maximization of yield in the upper Gulf must be established under an ecosystem-based management with all the uncertainties imposed by climate changes. This approach must be a priority on the stakeholders' agenda because, if it is not a priority, there is a risk that the fisheries in the upper Gulf will attain neither stability nor profitability in the future.

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Appendix 1. History of the main fisheries in the Gulf of California, Mexico.

Year	Event	Ref.
>1900	Only aboriginal Cucapá communities were fishing in the upper Gulf before 1500s reaching up to 20,000 people (2,4). Delta area of 780,000 ha (to decrease to 70,000 ha in 1990s; 3, 37).	2, 3, 4, 37,
1900-09	Seasonal fishing camps in the upper Gulf grew into families and communities: Puerto Peñasco, Golfo de Santa Clara and San Felipe became permanents (1). First Colorado River diversion started (3).	1, 3
1910-09	Totoaba adults fished for local consumption in Central Gulf (14).	38
1920-29	Sport fishing began in Puerto Peñasco with the first hotel for American tourists (2). Totoaba sport fishery began (11). Totoaba fishery in the central Gulf started to decline, so that 6 German fishermen followed totoaba migration to the upper Gulf (11). The Water diversion of the Colorado River is signed (6). Offshore shrimp fishery began with two US boats (14). Commercial totoaba fishery in the upper Gulf (5). In 1923 began shrimp fishery, with totoaba juveniles taken accidentally (14). Agreement between US and Mexico for totoaba (52). The most important changes in boats during the development of fishery in the GoC were the use of outboard motors for small boats which were formerly propelled by oars (39, 40).	2, 5, 6, 10, 14, 39, 40, 11,
1930-39	Hoover Dam became the first of 20 Major Dams on the Colorado River (6). 17 sardine boats modified for shrimp fishing (14). Bycatch of vaquita began (7). Physical and chemical conditions of the upper Gulf altered and affecting endemic species (totoaba and vaquita) and commercial species such as shrimp (52).	6, 14, 7, 52,
1940-49	Closed season for totoaba from 20/03/40 to 01/05/40 to protect spawners (52). Totoaba sport fishery declined (66). "Before and After World War II, American and Japanese ships took every school of tuna and every swarm of sardines they could, along with sea lions for pet food and sharks to use the livers to remedy iron-poor or tired-blood" (8 in 9). In 1946, the highest exportation of totoaba to the US market with 1,299 t of fillets (52). Completion of Highway 8 in 1942 and the railroad in 1947 linked the Mexican production of the UGC to US markets (1).	8, 9, 1, 52, 66,
1950-59	1950 shrimp fishery growth exponentially (14). 1955 a new Biosphere Reserve nuclear zone established, fishing in the mouth of the Colorado river is prohibited (10). Closed season for totoaba changed from 01/03 to 01/04 or 15/05 according to their abundances (52). Totoaba landings started to decline (52). Double-ring trawls introduced into the shrimp fishery (14). 1955 shrimp CPUE (Catch/Boat) has its maximum with 45 t (heads off) in Guaymas (central Gulf; 14).	14, 10, 52,
1960-69	The freshwater input to the upper Gulf stops due to completion of the Glenn Canyon Dam and filling of Lake Powell (12). Shrimp fishery expanded to the UGC (10). Sardine fish meal plants and canneries come to central Gulf (Guaymas) (53). Sardine landings started to decrease (53). Although, it has been prohibited by law, dynamite is also used to kill totoaba directly (41 in 39). Late of 60's Shrimp trawls fishermen gradually reduce mesh size (implies increase of bycatch)(10).	12, 10, 53, 14, 41, 39,

Appendix 1. Continuation.

Year	Event	Ref.
1970-74	Pacific sardine fishery collapsed and moved to central Gulf (53). Sardine fishing in the GoC was initiated on a massive scale in 1971 (67). Jumbo squid fishery in central Gulf began (54). High shrimp prices; government invest in boats, equipment and a harbor en Puerto Peñasco (1). Mexican immigration to the Gulf in a kind of 'Gold Rush' for shrimp, which was known as 'Pink Gold' (1). El Niño event (1972) (22). 73 species were collected from the bottom of the UGC (13 species are might be endemic), juveniles of most fish species occur in areas of high turbidity in the mouth of the Colorado River (36). Refuge zone declared in 1955 declared a reserve zone in 1974 banning all fishing in the UGC (32). 1970, there are around 12 large boats (shrimp trawlers) dedicated partially or exclusively to totoaba fishing in Puerto Peñasco and 18 small boats in Golfo of Santa Clara (38). There are no regulatory measures which fix catch quotas for totoaba or which limit the number of fishing units (38). Fishing totoaba is prohibited during the priod from the April 1 to May 15 of every year (39).	1, 14, 22, 36, 38, 53, 54, 39, 67, 32,
1975-79	Mexican Law protects totoaba; fishery banned (18). Totoaba listed as threatened under CITES (13). Drastic declines in totoaba, but commercial and sport fishing outlawed, but totoaba gillnetting continued until 1990s and it was a primary cause of incidental kills of vaquita (53). Mesh size regulation introduced in 1977 as a management measure in the shrimp trawl fishery (16 in 14). 1977, 28 Peruvian boats (120 t) entered the Gulf after the collapse of the Peruvian anchovy fishery (53). 1979 high squid abundance triggered increase in fleet size, Japanese vessels appeared (17). Lake Powell is now filled and some water can reach the upper Gulf during strong precipitation events (6). Monofilament gill nets became the tool of the panga fishermen; 5,000 - 7,000 pangas fishing in the Gulf (19). Institute of National fisheries (INP) began monitoring programs to evaluate shrimp spawning and recruitment each year until 1987 (14). 1978 saw onset of commercial exploitation of demersal resources in the GoC with 12 trawlers (43). 344, 000 tonnes of bycatch in the shrimp fishery from 1977-80 (43).	18, 13, 15, 16, 14, 17, 6, 19, 43, 53, 52,
1980-84	An average of 6 marlins a day were catching (in Cabo San Lucas, BCS, according to one fisherman; 20). Still fishing totoaba (38). 35 vaquitas killed per year (1985-1992) in gillnets (7). Shrimp landings were higher than normal – suggests that spawning in promoted in post El Niño conditions (54). More than 80% of the total catch of shrimp in Mexico (40,000 to 55,000 t heads on) is caught in the Gulf of California (14). The shrimp fleet doubled without any increase in the total catch and the catch per boat diminished from 39 t (heads off) per year in 1971 to 15 tonnes in 1980 (14). Expansion of the Pacific sardine fishery in the Gulf (53). Newly installed processing plants increased demand for Pacific sardine (53). Strong El Niño event (1982-83) and associated with an increase of water discharge from the Colorado River in the upper Gulf (22). Jumbo squid fishery collapsed (54). Seven species of cetacean have been recorded after a period (1986-87) of freshwater release in the upper Gulf (34).	20, 38, 7, 53, 22, 54, 34,

Appendix 1. Continuation.

Year	Event	Ref.
1985-89	From 1985 to 1993 over 200,000 sharks were killed (24). Late of 1980s near vanish of Pacific sharp nose shark (55). 1984, shrimp landings higher than normal - associated with El Niño conditions-(56). EEZ established (57). Anchovy first appeared in commercial landings (53). Collapse of shrimp industry at the end of 1980s (21). Drastic decline of Pacific sardine fishery in the Gulf (53). Catches of chano represents 16% of the finfish fishery in Puerto Peñasco and it growth to 86% in 1992 (51). 1989, a total of 816 'pangas' and 266 shrimp boats in the upper Gulf (64). 161 tonnes of totoaba poached in 1985 (↑)(64). High market price (US markets) for the totoaba meat, increases illegal fishing of this species (64).	24, 55, 56, 57, 53, 22, 21, 51, 64,
1990-94	Small boat fishermen in the upper Gulf began to hammer chano to supply the Asian market for surimi, the processed with 700 t processed in the Golfo of Santa Clara alone (15). From Jan to Oct 1993, 12 vaquitas were killed during 16,000 hours of chano fishing (el Golfo de Santa Clara small scale fleet around 200 pangas)(15). Total vaquita population is 400-500 individuals (44). Trawles forced to use turtle- and finfish excluder devices (15). Near collapse of shrimp fishery provoked diversification of small scale fishing activity and target species switch (6). Upper Gulf has a fleet around 600 pangas (21). 1993 for the firt time at least 35 vaquitas died accidentally in the fisheries each year (7). In 1992, the Mexican authorities banned the use of gillnets with a mesh size greater than 25 cm (45). Fishing improved significantly following Colorado River floods in the early 1980s, blue shrimp landings increased, and the Gulf corvina (*Cynoscion othonopterus*), a fish that had not been seen in the upper Gulf for 40 years, returned in large numbers.(21). Santa Clara, San Felipe and Puerto Peñasco's fleet were largely privatized during the 1993-94 season (21). Establishment of the upper Gulf of California/ Colorado River Delta Biosphere Reserve: Core Zone: all commercial fisheries banned except for traditional fishing by the Cucapá people in the delta and clam harvesting by local residents; buffer zone: increased regulations for most fisheries. (12). There was an increase of sport fishing in the upper Gulf, first tourist mega-project (hotel Plaza Las Glorias), today at least 13 mega-projects are planned for the UGC (1). 1994, a gillnet fleet backed by unknown financiers appeared in Sonora, fishermen and scientists say it slaughters thousands of shark solely for their fins ($US 300 a pound in Asian markets)(9). 1990, population of giant mantas in Southern Gulf had dwindled to nothing (victims of harpooning and gillnets)(25). The shark fishermen bait their nets with marine mammal meat (24). 1993 El Niño event linked to increased water discharge from the Colorado River, water release from Lake Powell (22). PROFEPA enforces activities in the Reserve (6). Shrimp bycatch ratio estimated at 1:10 (6).	15, 44, 21, 7, 45, 12, 1, 9, 25, 24, 22, 6,
1995-99	1995, almost no shark at all, the big shark processors moved to their next target (24). Nevertheless, the management plan, finalized in 1996, allows offshore trawling in the buffer zone of the Biosphere reserve; trawlers will be required to carry turtle-excluder devices (21). No fishing in the core area of the Biosphere Reserve, also, no trawling in estuaries or depths lower than 9m (26). Increase of shrimp landings after El Niño event and water delivered by the Colorado River (26). Shrimp trawlers started to use turtle and finfish excluder devises in the upper Gulf (26). Turtle excluder devices mandatory in commercial shrimp fishery (7). Only 20 new squid licenses recommended (68).	24, 21, 26, 7, 27, 68,

Appendix 1. Continuation

Year	Event	Ref.
1995-99	At least 70 species of fish, mollusks, crustaceans and echinoderms are regularly caught by the artisanal fleet, approximately 40% of these are designated for international market (27). Mexico created CIRVA: International Committee for the recovery of the Vaquita (26). 212,000 t of Monterrey sardine in central Gulf recorded pre-El Niño (59). 1997: 1,144 shrimp boats in the Gulf using two nets of 24 m (60). 1997, strong El Niño event (22). 1998, only 59,000 tonnes of Monterrey sardine recorded from the Central Gulf - drop associated with warm temperatures of El Niño 1997 (59). Water released from the Lake Powell into the UGC (6). 1995, most fishermen of the upper Gulf thought that the richness had declined between 70 to 80% (19). Increase of sardine landings associated with post El Niño cooler SST (59). The landings shrimp catches in UGC correlated significantly with Colorado River discharge (35). The spawning and nursery grounds of totoaba have been altered by control of the Colorado River flow and agricultural waste (negative impact on the survival of very early life stages of totoaba)(42). 1997 last census puts vaquita population at 567 individuals (47). 1998, CEDO published extensive research of inshore fisheries in the UGC (27). An atlas of abundance for the 17 most abundant fish species in the UGC was developed with a list of 98 fish species caught by trawlers (50).	59, 60, 22, 19, 5, 35, 42, 47, 50, 68,
2000	There were 200 (1993) pangas in the Gulf of Santa Clara that increase to 600 pangas in 2000 (26). CNP (Carta Nacional Pesquera) established to increase the fishing effort in the upper Gulf with 700 tons of shrimp per year, not including Puerto Peñasco (26). " It is difficult to know the number of boats fishing in the gulf (61). Mexican law makes it illegal to destroy seabed structure and use fishing methods with high bycatch rates (6). NAFS official list of marine fishes at risk of extinction include six species from the GoC (33). Delta maintains about 70,000 ha of wetland (6). The CNP (Carta Nacional Pesquera) disbanded bycatch of vaquitas must be lower than 0.2 /year (48). The GoC is the most productive region for fisheries in Mexico (51). 46,000 people living inside of the Biosphere Reserve, where fishing and tourism are the principal activities (51).	26, 61, 6, 33, 48, 51,
2001	More than 1,600 km of gillnet were sold in Sonora (central Gulf). 40,000 turtles are killed per year on the west Coast of Mexico (9). The high price of turtle meat and shark fins, founded on male folklore long predating (31). October: PROFEPA (Secretary of Environmental Protection) said that it was possible to remove the shrimp trawlers during 15 days from the Biosphere Reserve (16). WWF/CEDO meeting with gillnet fishers concluded that 75% of them in the upper Gulf were prepared to change fishing practice/ jobs (6). Closed season for shrimps was variable by area for the first time (61). A total of 1,500 small boats in the upper Gulf (46). The productivity of mollusk, *Mulina Coloradensis* of the delta system has fallen at least 95% since dams built (49). In the GoC the offshore shrimp fishery caught 87% of this resource, inshore 13% (51). An official government survey found 238 pangas (49% of the official number registered) in El Golfo de Santa Clara fishing without permit (65).	9, 31, 16, 6, 61, 46, 49, 51, 65,
2002	Mr. Jeronimo Ramos, the National Fisheries commissioner said about 1,200 permits existed for boats in the GoC and Pacific Ocean, estimating 20-30% of the catch was being taken illegally (9). "Fishermen, businessmen, scientists and even some federal officials say at least 12,000 unregulated fishing boats, probably more, now at large in the GoC (9). The long-liners land as much as 20 t a day of dorado in the Port of Guaymas alone, along with unrecorded illegal catches like sea turtles ($US 200 dlls a piece in Mexican black market)(9). Shrimp fleet haul up 10 pounds of life for every pound of shrimp (9). 2,500 t of shrimp inside of the Biosphere Reserve are "harvested" (probably 1,800 tonnes by trawl fleet and the rest by the inshore fleet)(26). Official shrimp season from Sept-Oct to Feb-March (26). 140 shrimp boats in the upper Gulf, but an undetermined number of boats from other parts (Guaymas, Topolobampo, Mazatlan, Yavaros) enter to the Reserve (26)."It is necessary to know the real number of pangas fishing without permission in the Gulf of Santa Clara (16). September: emergency law introduced prohibiting trawling and restricting the types of gillnets allowed introduced. Triggered a dispute with shrimp trawlers. Resolved in November, with an agreement allowing 130 trawlers in the Reserve (63).	9, 26, 16, 32, 62, 63,

Appendix 1. Continuation

Year	Event	Ref.
2003	PROFEPA confiscated 11,000 kg of turtle in the upper Gulf during 8 days (30). CONAPESCA gave 2,400 permits for shrimp fishing for the season 2002-03, but there are between 6,000 to 7,000 boats fishing shrimps in the GoC, all year round (including closed season)(31).; Fish brokers bought 150 to 200 tonnes of fish a week, today they buy 10 to 15 tonnes (19). Trawling activity banned in the Biosphere Reserve (16).	30, 19, 31, 16,

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Appendix 2. Diet matrix built for the 2000 trophic model of the UGC.

	Prey \ Predator	1	2	3	4	5	6	7	8	9	10	11	12
1	Sharks > 120 cm												
2	Sharks 120 cm	0.090											
3	Totoaba	0.002											
4	Toothed cetaceans	0.014											
5	Sea lions	0.090											
6	Vaquita	0.000											
7	Croakers	0.090	0.026	0.012	0.041								
8	Jacks			0.003	0.025								
9	Corvinas	0.080	0.001	0.002	0.002	0.011							
10	Serranids	0.027	0.024	0.007	0.002	0.107	0.014			0.006			
11	Scombrids	0.250	0.017	0.002	0.041								
12	Snappers				0.010		0.023						
13	Seabirds		0.001										
14	Rays												0.340
15	Flounders			0.120		0.041							
16	Wrasses		0.004							0.006			
17	Chano	0.120	0.037	0.130	0.013	0.016	0.009						0.009
18	Sea turtles		0.000										
19	Pre-adult Vaquita	0.000											
20	Grunts			0.251	0.195		0.129						
21	Gerreidae		0.094	0.002	0.076	0.064	0.007	0.009	0.232			0.018	
22	Guitarfish		0.031	0.074	0.006								0.217
23	Small demersal fish		0.032	0.058	0.010		0.028		0.306				0.345
24	Other fishes	0.230	0.301	0.033	0.201	0.175	0.118		0.194	0.164		0.086	
25	Octopus				0.052	0.068	0.055	0.010		0.011			
26	Stomatopods		0.032	0.080	0.062	0.177	0.347			0.025			
27	Juv. Totoaba					0.001							
28	Myctophids				0.017	0.040	0.024	0.010	0.248	0.091			
29	Baleen whales				0.000								
30	Crabs		0.247			0.011	0.071				0.010		
31	Squids		0.141		0.077	0.050	0.035				0.047		
32	Small pelagics		0.012	0.226	0.171	0.240	0.141		0.020	0.011	0.076	0.896	
33	Jellies												
34	Planktivorous birds												
35	Rock shrimp							0.041			0.169		0.027
36	Blue shrimp										0.072		0.016
37	Brown shrimp										0.004		0.001
38	Semi-sessile epibenthos							0.002			0.017		
39	Sea cucumber												0.034
40	Benthic meoifauna										0.581		
41	Sessile epibenthos										0.025		0.010
42	*Mulina coloradensis*												
43	Bivalves												
44	Juv. of Blue Shrimp												
45	Zooplankton												
46	Seagrasses												
47	Seaweeds												
48	Phytoplankton												
49	Macroalgae												
50	Detritus							0.927		0.686			

Appendix 2. Continuation.

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1															
2															
3															
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5															
6															
7															
8															
9															
10															
11															
12															
13			0.000												
14					0.006		0.004								
15															
16															
17															
18															
19															
20															
21				0.085			0.023								
22															
23		0.032		0.060							0.055	0.007			0.062
24		0.031		0.088			0.008					0.007			
25	0.172			0.073			0.021	0.010			0.022	0.128	0.064		0.002
26				0.039						0.006		0.122			0.010
27															
28			0.127	0.450								0.115			
29															
30	0.011	0.008		0.031	0.020		0.011	0.007	0.007	0.007	0.010	0.219			
31				0.068								0.116			
32			0.188	0.099								0.109			
33		0.000	0.156				0.034	0.011	0.024		0.011				
34															
35	0.017			0.002	0.056					0.014	0.039	0.003			0.015
36	0.013			0.002	0.016			0.012			0.001	0.001			0.015
37	0.001			0.002	0.001			0.001			0.001	0.001			0.015
38	0.108	0.025			0.098						0.002				0.027
39	0.006														
40	0.054	0.888			0.601	0.138	0.242	0.068	0.045	0.171	0.436				
41	0.609				0.130					0.093	0.048				0.029
42					0.000										
43					0.065					0.005	0.001				
44	0.009	0.016			0.008										
45									0.221		0.252	0.040	0.562	0.947	
46			0.172					0.052	0.046		0.024	0.006			
47			0.229			0.155		0.178			0.002				0.058
48									0.141				0.374	0.053	
49			0.129			0.023		0.030	0.027		0.036				0.021
50						0.684	0.658	0.631	0.489	0.705	0.060	0.128			0.747

Appendix 2. Continuation.

	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
1															
2															
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20															
21															
22															
23								0.000							
24															
25															
26	0.010							0.056							
27															
28	0.072		0.021												
29															
30					0.003			0.028							
31															
32	0.118		0.001												
33											0.170				
34															
35								0.029							
36					0.005						0.003				
37					0.001										
38					0.013	0.023									
39															
40				0.133	0.070		0.123	0.104			0.089				
41					0.029			0.026							
42															
43															
44								0.060							
45	0.752	1.000	0.978	0.217	0.357	0.344	0.327	0.121		0.166				0.100	0.100
46								0.121		0.001	0.005				
47				0.025				0.124	0.059	0.083	0.105				
48					0.214	0.372	0.163			0.106		0.400	0.600	0.600	0.900
49				0.046	0.035	0.013	0.016	0.028	0.118	0.113	0.095				
50	0.048			0.579	0.273	0.248	0.371	0.302	0.824	0.531	0.534	0.600	0.400	0.300	

Appendix 3. Diet matrix built for the 1980 trophic model of the UGC

	Prey \ Predator	1	2	3	4	5	6	7	8	9	10	11	12
1	Sharks > 120 cm	0.001											
2	Sharks 120 cm	0.220											
3	Totoaba	0.002											
4	Toothed cetaceans	0.015											
5	Sea lions	0.080											
6	Vaquita	0.000											
7	Croakers	0.080	0.021	0.039	0.074								
8	Jacks			0.009	0.093								
9	Corvinas	0.070	0.003	0.002	0.002	0.019							
10	Serranids	0.030	0.021	0.024	0.049	0.044	0.008						
11	Scombrids	0.270	0.001		0.001								
12	Snappers				0.002		0.010						
13	Seabirds		0.000										
14	Rays			0.158									0.334
15	Flounders			0.012		0.013							0.006
16	Wrasses		0.007							0.008			
17	Chano		0.011	0.133	0.163	0.020	0.002					0.047	
18	Sea turtles		0.000										
19	Pre-adult Vaquita	0.000											
20	Grunts			0.302	0.150		0.127						
21	Gerreidae		0.066	0.001	0.067	0.032	0.011	0.002	0.331				
22	Guitarfish		0.042	0.233	0.008								0.334
23	Small demersal fish			0.001			0.005		0.310				0.265
24	Other fishes	0.160	0.227	0.074	0.145	0.382	0.148	0.010	0.059	0.037		0.027	0.015
25	Octopus				0.037	0.102	0.191	0.005		0.013			
26	Stomatopods			0.012	0.025	0.269	0.213			0.010			
27	Juv. Totoaba					0.000							
28	Myctophids								0.270	0.083		0.793	
29	Baleen whales	0.000			0.000								
30	Crabs		0.352			0.017	0.102	0.001			0.008		
31	Squids		0.250		0.186	0.102	0.123		0.030		0.060		
32	Small pelagics						0.060			0.001	0.010	0.133	
33	Jellies												
34	Planktivorous birds												
35	Rock shrimp										0.001		0.002
36	Blue shrimp							0.000			0.026		0.035
37	Brown shrimp												0.000
38	Semi-sessile epibenthos							0.002			0.022		
39	Sea cucumber												0.002
40	Benthic meiofauna										0.647		
41	Sessile epibenthos										0.031		0.008
42	*Mulina coloradensis*												
43	Bivalves												
44	Juv. of Blue Shrimp												
45	Zooplankton												
46	Seagrasses												
47	Seaweeds												
48	Phytoplankton												
49	Macroalgae												
50	Detritus							0.979		0.850	0.194		

Appendix 3. Continuation.

	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1															
2															
3															
4															
5															
6															
7			0.001												
8															
9															
10															
11															
12															
13						0.001									
14		0.001	0.031							0.004					
15		0.016													
16		0.007													
17				0.001											
18															
19															
20				0.001											
21		0.008					0.195			0.026					
22															
23		0.106		0.023		0.010	0.011						0.063		
24	0.016	0.013	0.009	0.017		0.025		0.009		0.062			0.039		0.014
25		0.035	0.014	0.164			0.110	0.009		0.011	0.005			0.024	0.130
26	0.077	0.013					0.007						0.010		0.013
27															
28	0.841						0.625								
29															
30		0.013	0.012	0.012	0.003	0.012	0.019	0.005		0.010	0.002	0.002	0.007	0.011	0.243
31							0.033							0.001	0.188
32	0.067						0.002								0.009
33					0.000	0.259				0.039	0.001	0.048		0.012	
34															
35													0.007	0.012	
36		0.001	0.001	0.008	0.001			0.009			0.005	0.001	0.002	0.001	
37		0.000	0.000										0.001	0.001	
38		0.035	0.034	0.161	0.022			0.091			0.010	0.019	0.085	0.002	
39		0.001						0.001				0.001			
40		0.053	0.034	0.080	0.771			0.467	0.139	0.277	0.067	0.193	0.289	0.668	
41			0.002	0.520	0.022			0.065			0.031		0.158	0.053	
42		0.000						0.000							
43		0.000						0.001					0.001	0.000	
44				0.014	0.000			0.000			0.000				
45												0.032		0.090	
46					0.004	0.233		0.009			0.051	0.193		0.027	0.081
47					0.004	0.311		0.028	0.156		0.175	0.193		0.002	
48															
49						0.148		0.033	0.015		0.032	0.030		0.029	
50		0.696	0.861		0.174			0.272	0.690	0.571	0.621	0.289	0.338	0.067	0.323

Appendix 3. Continuation.

	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
1																
2																
3																
4																
5																
6																
7																
8																
9																
10																
11																
12																
13																
14																
15																
16																
17																
18																
19																
20																
21																
22																
23									0.000							
24																
25	0.001															
26	0.009								0.019							
27																
28		0.223														
29																
30	0.001															
31		0.002														
32		0.015														
33		0.017														
34																
35	0.006								0.011							
36	0.011					0.007	0.000	0.000								
37	0.004															
38	0.019					0.017	0.028	0.027								
39																
40	0.072				0.139	0.089	0.124	0.166	0.239			0.190				
41	0.021					0.037			0.025							
42																
43																
44	0.000								0.000							
45		0.743	0.995	1.000	0.195	0.308	0.287	0.289	0.021		0.083	0.106	0.130	0.118	0.329	0.200
46	0.036								0.116		0.001	0.013				
47	0.041				0.026				0.119	0.061	0.093	0.013				
48			0.005			0.006	0.008	0.008							0.088	0.800
49	0.022				0.034	0.029	0.011	0.012	0.019	0.083	0.099					
50	0.760				0.606	0.508	0.542	0.498	0.431	0.856	0.724	0.678	0.870	0.882	0.584	

Appendix 4. Diet matrix built for the 1950 trophic model of the UGC.

	Prey \ Predator	1	2	3	4	5	6	7	8	9	10	11	12
1	Sharks > 120 cm	0.001											
2	Sharks 120 cm	0.178											
3	Totoaba	0.071											
4	Toothed cetaceans	0.011											
5	Sea lions	0.060											
6	Vaquita	0.000											
7	Croakers	0.035			0.272		0.282				0.092		
8	Jacks			0.035	0.340								
9	Corvinas	0.082	0.127	0.046	0.105	0.047					0.092		
10	Serranids	0.039	0.177	0.232	0.154	0.076	0.042						
11	Scombrids	0.329		0.246	0.042	0.047							
12	Snappers						0.118				0.088		
13	Seabirds	0.000	0.000										
14	Rays												0.072
15	Flounders												
16	Wrasses		0.021								0.020		
17	Chano	0.037	0.037		0.041		0.025			0.031		0.099	
18	Sea turtles	0.001											
19	Pre-adult Vaquita	0.000			0.000								
20	Grunts			0.398			0.163						
21	Gerreidae		0.027				0.010		0.631				
22	Guitarfish												0.061
23	Small demersal fish							0.083					0.813
24	Other fishes	0.151	0.412			0.226			0.279			0.346	
25	Octopus					0.236	0.224	0.036		0.022	0.004		
26	Stomatopods			0.044		0.230	0.118	0.165		0.017	0.197	0.023	
27	Juv. Totoaba		0.001										
28	Myctophids											0.247	
29	Baleen whales				0.000								
30	Crabs		0.051				0.018				0.000		
31	Squids		0.149		0.046	0.139		0.083	0.029			0.049	
32	Small pelagics								0.062			0.236	
33	Jellies												
34	Planktivorous birds												
35	Rock shrimp												
36	Blue shrimp										0.011		0.049
37	Brown shrimp												
38	Semi-sessile epibenthos												
39	Sea cucumber												0.005
40	Benthic meiofauna							0.044					
41	Sessile epibenthos												
42	*Mulina coloradensis*												
43	Bivalves												
44	Juv. of Blue Shrimp							0.004					
45	Zooplankton												
46	Seagrasses												
47	Seaweeds												
48	Phytoplankton												
49	Macroalgae							0.007					
50	Detritus							0.579		0.930	0.497		

Appendix 4. Continuation.

	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1																
2																
3																
4																
5																
6																
7																
8																
9	0.104															
10																
11																
12		0.020	0.012			0.011				0.045					0.024	
13						0.022										
14																
15		0.001	0.007	0.039												
16										0.045						
17	0.093															
18																
19																
20				0.039												
21				0.079			0.497									
22																
23			0.036	0.118						0.089						
24	0.363		0.146							0.089						
25		0.036	0.008	0.018			0.051	0.001		0.006	0.004				0.012	
26	0.009	0.166	0.088	0.157			0.383	0.090		0.089	0.083		0.011		0.123	
27																
28																
29																
30	0.019					0.014	0.013			0.006	0.002	0.002	0.007		0.127	
31	0.155														0.161	
32	0.207						0.031									
33	0.051				0.000	0.163	0.026		0.018		0.001	0.046		0.117	0.024	
34																
35													0.001	0.000		
36		0.001	0.000								0.001	0.000	0.001			
37		0.000	0.000					0.000	0.000			0.000	0.000			
38				0.034				0.011					0.065			
39																
40					0.202			0.184		0.009	0.011	0.043	0.052	0.281		
41				0.110									0.067	0.006		
42		0.000						0.000					0.000			
43		0.000						0.001					0.001			
44				0.012	0.000											
45														0.000		0.833
46						0.083						0.010		0.011	0.056	
47						0.091			0.026			0.028				
48																0.167
49						0.109		0.081	0.013		0.041	0.029		0.033		
50		0.776	0.703	0.394	0.798	0.508		0.632	0.943	0.623	0.858	0.842	0.794	0.552	0.473	

Appendix 4. Continuation.

	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
1																
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13																
14																
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16																
17																
18																
19																
20																
21																
22																
23			0.108													
24																
25		0.001														
26		0.008	0.108													
27																
28			0.108													
29																
30																
31	0.011															
32			0.082													
33			0.108													
34																
35		0.001	0.011							0.002						
36			0.011													
37		0.004					0.001	0.001								
38																
39		0.001														
40									0.042	0.044						
41																
42																
43										0.000						
44										0.000						
45	0.982		0.467	0.823	1.000	0.131	0.144	0.126	0.155				0.119	0.135	0.124	0.464
46										0.030						
47										0.040	0.052					
48	0.007			0.177			0.004	0.005	0.007				0.110	0.071	0.069	0.121
49		0.019				0.030	0.020	0.008	0.009	0.016	0.070	0.093				
50		0.966				0.839	0.831	0.861	0.787	0.868	0.879	0.907	0.771	0.795	0.806	0.415

Appendix 5.Continuation.

6. Fishing Areas (see attached map):
7. Fishing seasons for main target species:
(a)____
(b) ____
(c) ____

8. What gears are you using ? ____
9. In which year did you begin to fish? __________
10. Last season fishing ________
11. Number of years fishing ? (0-5) (5-10) (10-20) (20-30) (30-40) (40+)
12. Number of generations their family has been fishing?
13. Always in this region?
14. What percentage of the catch is discarded ?
a) little (less than 10%) _______
b) moderate (10-40%) _______
c) high (> 40%). ________

15. Do you consider that your catches were higher in the past than the catches in the present?

16. Were the abundance of seabirds and marine mammals higher than today?
17. Do you have any example of this trend?

18. Other Comments:

19. Is any species disappeared during your career?

The following questions were applied for the principal species / groups of fish, seabirds and marine mammals living in the upper Gulf of California..

---

20. The abundance of sea lions has increased in the last:
a) 10 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

21. Has the abundance of sea lions diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%]. [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

22. The abundance of vaquita has increased in the last:
a) 10 years....................[< 1x] , [1-3x], [3-10x], [>10x], [no change]
b) 20 years....................[< 1x] , [1-3x], [3-10x], [>10x], [no change]
c) 30 years....................[< 1x] , [1-3x], [3-10x], [>10x], [no change]
d) 40 years....................[< 1x] , [1-3x], [3-10x], [>10x], [no change]

Appendix 5. Continuation. .

23. Has the abundance of vaquita diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%]. [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

24. The abundance of dolphins has increased in the last:
a) 10 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

25. Has the abundance of dolphins diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%]. [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

26. The abundance of whales has increased in the last:
a) 10 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

27. Has the abundance of whales diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%], [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

28. The abundance of sharks has increased in the last:
a) 10 years...................[< 1x] , [1-3x], [3-10x], [>10x], [no change]
b) 20 years...................[< 1x] , [1-3x], [3-10x], [>10x], [no change]
c) 30 years...................[< 1x] , [1-3x], [3-10x], [>10x], [no change]
d) 40 years...................[< 1x] , [1-3x], [3-10x], [>10x], [no change]

29. Has the abundance of sharks diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%]. [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

30. The abundance of totoaba has increased in the last:
a) 10 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

Appendix 5. Continuation

31. Has the abundance of totoaba diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%]. [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

32. The abundance of snappers has increased in the last:
a) 10 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

33. Has the abundance of snappers diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%]. [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

34. The abundance of flatfish has increased in the last:
a) 10 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

35. Has the abundance of flatfish diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%]. [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

36. The abundance of shrimp has increased in the last:
a) 10 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

37. Has the abundance of shrimp diminished in the last:
a)10 years.................[<50%], [10-50%], [>10%], [no change]
b)20 years.................[<50%], [10-50%], [>10%], [no change]
c)30 years.................[<50%], [10-50%], [>10%]. [no change]
d)40 years.................[<50%], [10-50%], [>10%], [no change]

38. The abundance of crabs has increased in the last:
a) 10 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years....................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

Appendix 5. Continuation

39. Has the abundance of crabs diminished in the last:
a)10 years................[<50%], [10-50%], [>10%], [no change]
b)20 years................[<50%], [10-50%], [>10%], [no change]
c)30 years................[<50%], [10-50%], [>10%]. [no change]
d)40 years................[<50%], [10-50%], [>10%], [no change]

40. The abundance of sardines-anchovies has increased in the last:
a) 10 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

41. Have the abundances of sardines-anchovies diminished in the last:
a)10 years................[<50%], [10-50%], [>10%], [no change]
b)20 years................[<50%], [10-50%], [>10%], [no change]
c)30 years................[<50%], [10-50%], [>10%]. [no change]
d)40 years................[<50%], [10-50%], [>10%], [no change]

42. The abundance of seabirds has increased in the last:
a) 10 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

43. Has the abundance of seabirds diminished in the last:
a)10 years................[<50%], [10-50%], [>10%], [no change]
b)20 years................[<50%], [10-50%], [>10%], [no change]
c)30 years................[<50%], [10-50%], [>10%]. [no change]
d)40 years................[<50%], [10-50%], [>10%], [no change]

44. The abundance of chano has increased in the last:
a) 10 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
b) 20 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 30 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 40 years...................[< 1x] , [no change], [1-3x], [3-10x], [>10x]

45. Has the abundance of "*chano*" diminished in the last:
a)10 years................[<50%], [10-50%], [>10%], [no change]
b)20 years................[<50%], [10-50%], [>10%], [no change]
c)30 years................[<50%], [10-50%], [>10%]. [no change]
d)40 years................[<50%], [10-50%], [>10%], [no change]

Other Comments:

Appendix 6. Price market estimated for each fleet operating in the upper Gulf of California during 2000. Prices are expressed in $US dollars/kg

Group Name	Offshore shrimp Trawlers	Offshore Finfish	Art.shrimp (2")	Art.Gillnet (2.5-4")	Art. Gilnet (> 4")	Long-liners	Traps	Hooka divers
Sharks	0	0	0	0	0.9	0.9	0	0
Sharks (< 120cm)	0	0	0	0.9	0.9	0.9	0	0
Totoaba	0	0	0	0	0	0	0	0
Toothed cetaceans	0	0	0	0	0	0	0	0
Sea lions	0	0	0	0	0	0	0	0
Vaquita	0	0	0	0	0	0	0	0
Croakers	0	0	0.2	0.2	0	0	0	0
Jacks	0	0	0.25	0.25	0	0	0	0
Corvinas	0	0	0	0.8	0.8	0.8	0	0
Serranids	0	0	0	2	2	2	0	0
Scombrids	0	0	0	0.8	0.8	0.8	0	0
Snappers	0	0	0	0.85	0	0	0	0.85
Seabirds	0	0	0	0	0	0	0	0
Rays	0	0	0	0.7	0.7	0	0	0
Flounders	0	0	0	1.85	1.85	1.85	0	1.85
Wrasses	0	0	0	0	0	2.2	0	0
Chano	0	0	0	0.35	0.35	0	0	0
Sea turtles	0	0	0	0	0	0	0	0
Pre-adult Vaquita	0	0	0	0	0	0	0	0
Grunts	0	0.05	0	0.15	0	0	0	0
Gerreidae	0	0	0	0.17	0	0	0	0
Guitarfish	0	0	0	0	0.65	0.65	0	0
Small dem. fish	0	0	0	0	0	0	0	0
Other fishes	0	0	0	0	0.3	0.3	0	0
Octopus	0	0	0	0	0	0	0	1.8
Stomatopods	0	0	0	0	0	0	0	0
Juv. Totoaba	0	0	0	0	0	0	0	0
Myctophids	0	0	0	0	0	0	0	0
Baleen whales	0	0	0	0	0	0	0	0
Crabs	0	0	0	0	0	0	0.8	0.8
Squids	0	0.15	0	0.2	0	0	0	0
Small pelagics	0	0.1	0	0	0	0	0	0
Jellies	0	0	0	0	0	0	0	0
Planktivorous birds	0	0	0	0	0	0	0	0
Rock shrimp	2.5	0	2.5	0	0	0	0	0
Blue shrimp	8	0	10	0	0	0	0	0
Brown shrimp	6	0	6	0	0	0	0	0
Semi-sessile epibenthos	0	0	0	0	0	0	0	0.8
Sea cucumber	0	0	0	0	0	0	0	3
Benthic meoifauna	0	0	0	0	0	0	0	0
Sessile epibenthos	0	0	0	0	0	0	0	3.5
M. coloradensis	0	0	0	0	0	0	0	0

Bivalves	0	0	0	0	0	0	0	6.5
Juv. of Blue Shrimp	0	0	0	0	0	0	0	0
Zooplankton	0	0	0	0	0	0	0	0
Seagrasses	0	0	0	0	0	0	0	0
Seaweeds	0	0	0	0	0	0	0	0
Phytoplankton	0	0	0	0	0	0	0	0
Macroalgae	0	0	0	0	0	0	0	0

Appendix 7. Fishing costs estimated for each fleet operating in the upper Gulf of California during 2000. These costs were employed in the 2000 Ecopath model of the region.

Name of fleet	Fixed cost	Effort related	Sailing cost	Profit	Total value
	(%)	cost (%)	(%)	(%)	(%)
Offshore shrimp trawl	15	25	20	40	100
Offshore finfish fishery	15	15	25	45	100
Artisanal Shrimp (gillnet 5 cm)	10	15	15	60	100
Artisanal Gillnet (6-10 cm)	10	15	10	65	100
Artisanal Gillnet <10 cm	10	15	15	60	100
Artisanal long-liners	12	20	20	48	100
Traps	3	12	6	79	100
Hooka divers	5	14	10	71	100

Appendix 8. 76 Scenarios employed during the search for optimum fishing in the upper Gulf of California. This analysis was based on the 2000 mass-balanced model presented in Chapter II. Each scenario has a different combination of the weights of the six objectives used in the 76 scenarios.

Scenario	Economic	Social	Ecological	Rebuiling		
				(all groups)	Totoaba	Vaquita
1	0	0	0	1	0	0
2	0	0	0	1	0	2
3	0	0	0	1	2	1
4	0	0	0	1	2	0
5	0	0	0	1	0	3
6	0	0	0	1	4	1
7	0	0	1	0	0	0
8	0	0	2	0	0	0
9	0	1	3	0	0	0
10	0	2	0	0	0	0
11	0	3	0	0	0	0
12	0	4	0	0	0	0
13	1	0	0	0	0	0
14	2	0	0	0	0	0
15	3	0	0	0	0	0
16	4	0	0	0	0	0
17	0	0	1	1	1	2
18	0	0	1	2	2	2
19	0	0	1	3	2	2
20	0	0	2	2	2	2
21	0	0	3	2	2	2
22	0	0	3	1	2	2
23	0	1	1	0	0	0
24	0	1	2	0	0	0
25	0	1	3	0	0	0
26	0	2	1	0	0	0
27	0	2	2	0	0	0
28	0	2	3	0	0	0
29	0	3	1	0	0	0
30	0	3	2	0	0	0
31	0	3	3	0	0	0
32	1	1	0	0	0	0
33	1	2	0	0	0	0
34	1	3	0	0	0	0
35	2	1	0	0	0	0
36	2	2	0	0	0	0
37	2	3	0	0	0	0
38	3	1	0	0	0	0
39	3	2	0	0	0	0
40	3	3	0	0	0	0
41	0	1	1	1	1	0

Appendix 8. Continuation.

42	0	1	1	1	1	1
43	0	1	1	1	2	2
44	0	1	1	2	2	2
45	0	1	1	3	3	3
46	0	1	2	1	2	2
47	0	1	3	2	2	2
48	0	2	1	1	2	2
49	0	3	2	1	2	2
50	1	1	1	2	2	2
51	1	1	1	3	2	2
52	1	1	2	3	1	1
53	1	1	3	1	1	1
54	1	2	3	1	2	2
55	1	3	3	2	2	2
56	1	3	3	3	2	2
57	2	1	1	1	2	2
58	2	1	1	2	1	0
59	2	1	1	2	1	1
60	2	1	1	2	2	2
61	1	1	3	2	2	2
62	1	1	4	2	2	2
63	1	1	5	0	0	0
64	1	0	5	0	0	0
65	1	0	2	1	1	1
66	0	0	6	0	0	0
67	0	0	10	0	0	0
68	0	0	40	0	0	0
69	10	0	0	0	0	0
70	5	0	0	0	0	0
71	0	10	0	0	0	0
72	0	5	0	0	0	0
73	0	3	0	0	0	0
74	0	0	0	10	10	10
75	0	0	0	5	5	5
76	0	0	0	20	20	20

Appendix 9. Summary of the sources of information employed for the functional groups in the 2000s Ecopath model in the upper Gulf of California. See references for complete citations.

2000s model	Biomass	P/B	Q/B	Diet
Sharks> 120 cm	4, 42	1	2	3, 58
Sharks < 120 cm	4	1	1	3, 58
Toothed cetaceans	5, 90	6, 86	7	6
Totoaba	4	10, 95	11, 96	11, 94
Sea lions and other pinnipeds	13, 83	14, 86	7	15
Vaquita	8, 61	12, 61, 94	9	29
Sciaenids	4	16	17	18, 58
Carangids	42	19	19	20, 58
Corvinas	4	18	18	18, 58
Groupers	4	21	22	88, 58
Scombrids	4	24	25	26, 58
Lutjanids	4,	93	27	27, 58
Seabirds	28, 68	23	30	68
Rays	4	16	31	32, 58
Guitarfish	4	16	33	32, 58
Flounders	4	34	34	35, 58
Wrasses	4,54,	16	36	36, 58
Grunts	4	37	17	38, 58
Chano	4	16	18	23, 58
Sea turtles	-	91	91	92
Pre-adult vaquita	-	86	7	Supposed
Octopus	54	92	22	40
Small demersal	4, 54,	16	17	41, 58
Gerreidae	42	16	17	94, 58
Other Fishes	4, 42	94	17	23, 89, 58
Stomatopods	43	43	69	44
Juv. totoaba	4	-	11	45
Myctophids	-	16	17	46, 58
Baleen whales	5, 85, 90	6, 86	7	84
Crabs	4	41	17	47, 78
Squids	54	39	17	79
Small pelagics	42	16	48	49, 87
Jellies	50, 54	51	-	52
Planktivorous birds	53	-	55	55
Rock shrimp	54, 56	94	17	56
Blue shrimp	75	57	17	76
Brown shrimp	75	96	17	76
Semi-sessile epibenthos	50, 42, 54, 82	51	17	94
Sea cucumber	54, 84	94	17	77
Benthic meiofauna	80, 81	59	59	41
Sessile epibenthos	50, 42, 54, 82	51	17	94
Mulina coloradensis	60	-	22	60
Bivalves	54	51	17	58

Appendix 9. Continuation.

2000s model	Biomass	P/B	Q/B	Diet
Juv. Blue shrimp	-	-	74	73
Zooplankton	62, 71, 72	41	63	63
Seagrasses	-	70		
Seaweeds	-	41		
Phytoplankton	64	65		
Macroalgae	66	67		
Detritus	17			

References cited in appendix 9:

(1) Compagno, 1999. (2) Compagno, 1995. (3) Galván-Magaña & Niehnhuis, 1989. (4) CRIP-Ensenada, 1995. (5) Silber *et al.* 1994. (6) Cetacea, 2001. (7) IMMA, 2001. (8) Jaramillo-Legorreta, 1999. (9) D'Agrosa *et al.* 2000. (10) Cisneros-Mata *et al.* 1995. (11) Román-Rodríguez, 1997. (12) D'Agrosa *et al.* 1995. (13) Zavala-González and Mellink, 1997. (14) Lluch-Belda, 1970. (15) García, 1991. (16) Pauly, 1980. (17) Pauly, 1986. (18) Chao, 1995. (19) Smith-Vaniz, 1995. (20) Craig, 1960. (21) Arreguín-Sánchez *et al.* 1996. (22) Pauly *et al.* 1993. (23) Arreguín-Sánchez, *et al.*2002. (24) Collette, 1995. (25) Collette and Russo, 1984. (26) Collette, 2003. (27) Rojas-Herrera and Chiapa-Carrera, 2002. (28) Mellink *et al.* 1996. (29) Brownell, 1986. (30) Velarde *et al.* 1994. (31) McEachran, 1995a. (32) Talent, 1982. (33) McEachran, 1995b. (34) Hensley, 1995. (35) Arellano-Martínez *et al,* 1997. (36) Hobson, 1976. (37) McKay and Schneider, 1995. (38) Watson, 1996. (39) Baddyr, 1991. (40) CephBase, 2001. (41) Chávez *et al.* 1993. (42) Pérez-Mellado, 1980. (43) Hendrix, 1990. (44) Crustacean, 2001. (45) Flannagan and Hendrickson, 1976. (46) Moser and Ahlstrom, 1996. (47) Romero, 1980. (48) Whitehead *et al.*, 1988. (49) Molina and Manríquez, 1997. (50) Félix-Pico, 1973. (51) Brey, 1999. (52) Alvariño, 1969. (53) Peresbarbosa and Mellink, 1994. (54) Félix-Pico, 1975. (55) Velarde *et al.* 1994. (56) López-Martínez *et al* 1999. (57) Aragón-Noriega, 2000. (58) Fishhbase, 2006 (59) Salazar-Vallejo, 1990. (60) Kowaleski *et al.* 2001. (61) D'Agrosa *et al.* 2000. (62) Farfán and Alvárez, 1992. (63) García-Pámanes and Lara-Lara, 2001. (64) Millán-Nuñez *et al.* 1999. (65) Millán-Nuñez, 1992. (66) Littler and Littler 1981. (67) Stewart and Norris, 1981. (68) Mellink *et al.* 1997. (69) Barbosa-Ledesma *et al.* 2000. (70) Meling-López and Ibarra-Obando, 1999. (71) Brinton *et al.* 1986. (72) Hernández-Trujillo and Esquivel-Herrera, 1989. (73) Aragón-Noriega and García-Juárez, 2002. (74) Aragón-Noriega & Calderón-Aguilera, 2001. (75) Aragón-Noriega *et al.* 1999. (76) López-Martinez *et al.* 2003. (77) Brucker *et al.* 2003. (78) Villareal-Chávez, 1992. (79) Squires and Barragán, 1991. (80) Villareal-Chávez and Carmona-Cedillo, 1999. (81) Fernández-Alamo, 1992. (82) Hendrix, 1985. (83) Aurieoles *et* al. 1993. (84) Tershy *et al.* 1993. (85) Villa, 1986. (86) Vidal and Gallardo-Reynoso, 1996. (87) Gallardo-Cabello *et al.* 1991. (88) Dale *et al.* 1984. (89) Abitia-Cardenas *et al.* 1990. (90) Silber, 1990. (91) Polovina, 1984. (92) Optiz, 1993. (93) Rojo *et al.* 1999. (94) Morales-Zarate *et al.* 2004. (95) Pedrín-Osuna *et al.* 2001.

Appendix 10. Summary of the sources of information employed for the functional groups in the 1980s Ecopath model in the upper Gulf of California. See references for complete citations.

1980s model	Biomass	P/B	Q/B	Diet
Sharks> 120 cm	1	2	3	4, 34
Sharks < 120 cm	1	2	2	4, 34
Toothed cetaceans	1	5	6	5
Totoaba	7	8	9	8
Sea lions and other pinnipeds	1	10	13	11
Vaquita	12	12	15	14, 38
Sciaenids	39	16	17	18, 34
Carangids	1	19	19	20, 34
Corvinas	39, 42	18	18	18, 34
Groupers	39, 42	21	22	23, 24
Scombrids	1	24	25	26, 34
Lutjanids	1	27	28	28, 34
Seabirds	1	29	30	31
Rays	39, 42	16	32	32, 34
Guitarfish	-	16	32	32, 34
Flounders	39, 42	33	33	33, 34
Wrasses	-	16	34	34, 36
Grunts	-	-	36	34, 36
Chano	-	16	18	29, 34
Sea turtles	-	-	17	37
Pre-adult vaquita	-	-	38	Supposed
Octopus	-	-	40	40
Small demersal	-	16	17	34, 41
Gerreidae	42	9	9	9, 34
Other Fishes	39, 42	16	17	9, 34
Stomatopods	39, 45	-	45	45, 46
Juv. totoaba	47	-	48	48
Myctophids	-	16	17	9, 34
Baleen whales	1	-	6	49, 50
Crabs	39	9	46	9, 46
Squids	39	-	40	40
Small pelagics	42	16	34	34, 51
Jellies	39	52	-	53
Planktivorous birds	1	-	54	54
Rock shrimp	39	9	17	9, 55
Blue shrimp	39	65	9	9, 56
Brown shrimp	39	9	9	9, 56
Semi-sessile epibenthos	-	52	17	9, 21
Sea cucumber	-	41	17	9
Benthic meiofauna	-	57	57	41
Sessile epibenthos	-	52	17	9
Mulina coloradensis	58	--	22	58
Bivalves	39	52	17	58

Appendix 10. Continuation.

1980s model	**Biomass**	**P/B**	**Q/B**	**Diet**
Juv. Blue shrimp	59	-	59	59
Zooplankton	60	9	61	61
Seagrasses	-	63	-	-
Seaweeds	-	63	-	-
Phytoplankton	62	64	-	-
Macroalgae	43	43	-	-
Detritus	17	-	-	-

References cited in appendix 10:

(1) Local fishers Knowledge, 2003 (see chapter III for details). (2) Compagno, 1999. (3)) Compagno, 1995. (4) Galván-Magaña & Niehnhuis, 1989. (5) Vidal and Gallardo, 1996. (6) IMMA, 2001. (7) CRIP-Ensenada, 1995. (8) Garcia, 1976. (9) Morales *et al.* 2004. (10) Lluch-Belda, 1970. (11) Zavala-González and Mellink, 1997. (12) D'Agrosa *et al.* 2000. (13) García-Rodriguez, 1999. (14) Brownell, 1986 (15) Cetacea, 2001. (16) Pauly, 1980. (17) Pauly, 1986. (18) Chao, 1995. (19) Smith-Vaniz,1995. (20) Craig, 1960. (21) Arreguín-Sánchez *et al.* 1996. (22) Pauly *et al.* 1993. (23) Dale *et al.*, 1984. (25) Collette and Russo, 1984. (26) Collette, 2003. (27) Rojo-Vázquez *et al.*, 1999. (28) Rojas-Herrera and Chiapa-carrera, 2002. (29) Arreguín-Sánchez *et al.*, 2002. (30) Velarde *et al.* 1994. (31) Mellink *et al.* 1997. (32) McEachran, 1995a, b. (34) Hensley, 1995. (34) FishBase, 2006. (35) Hobson *et al*, 1976 (36) McKay and Scheiner, 1995. (37) Optiz, 1993. (38) Ortiz, 1999. (39) Félix-Pico, 1976. (40) CephBase, 2001. (41) Chávez *et al.* 1993. (42) Pérez-Mellado, 1980. (43) Stewart and Norris, 1981. (44) Abítia-Cárdenas *et al.*, 1990. (45) Hendrix, 1985. (46) Crustacean, 2001. (48) flannagan and Hendrickson, 1976. (49) Vidal *et al.* 1999. (50) Cetacea, 2001. (51) Whitehead *et al.*, 1988. (52) Brey, 1999. (53) Alvariño, 1969. (54) Velarde *et al.* 1994. (55) López-Martínez *et al* 1997. (56) Aragón-Noriega, 2000. (57) Salazar-Vallejo, 1990. (58) Kowaleski *et al.* 2000. (59) Aragón-Noriega and Calderón-Aguilera, 2001. (60) Brinton *et al.* 1986. (61) García-Pamanes and Lara-lara, 2001. (62) Valdéz-Holguín, 1985. (63) Meling-López and Ibarra-Obando, 1999. (64) Millán-Nuñez, 1992. (65) García-Gómez, 1976.

Appendix 11. Summary of the sources of information employed for the functional groups in the 1950s Ecopath model in the upper Gulf of California. See references for complete citations.

1950s model	Biomass	P/B	Q/B	Diet
Sharks> 120 cm	1	7	8	9, 10
Sharks < 120 cm	1	7	7	9, 10
Toothed cetaceans	1	11	12	11
Totoaba	2	13	14	13
Sea lions and other pinnipeds	1	15	16	17
Vaquita	1	18	19	20, 21
Sciaenids	1	22	6	10, 23
Carangids	1	24	24	10, 23
Corvinas	1	23	23	10, 23
Groupers	-	26	27	10, 28
Scombrids	1	29	30	10, 31
Lutjanids	-	32	33	10, 33
Seabirds	1	34	35	36
Rays	1	22	37	10, 37
Guitarfish	-	38	38	10, 38
Flounders	1	22	38	10, 38
Wrasses	-	22	10	10
Grunts	-	22	39	10, 39
Chano	1	22	23	10, 23
Sea turtles	1	-	40	40
Pre-adult vaquita	-	-	20	Supposed
Octopus	-	-	41	41
Small demersal	-	22	6	10, 14
Gerreidae	-	14	14	10, 14
Other Fishes	-	22	6	10, 14, 34
Stomatopods	-	-	43	42
Juv. totoaba	-	-	44	44
Myctophids	-	22	6	10, 14
Baleen whales	1	-	12	12, 14, 45
Crabs	1	14	43	14, 43
Squids	1	-	42	41
Small pelagics	1	22	10	10
Jellies	-	46	-	46
Planktivorous birds	1	-	47	47
Rock shrimp	1	14	6	14, 48
Blue shrimp	1	49	14	14, 48
Brown shrimp	1	14	14	14, 48
Semi-sessile epibenthos	-	46	6	14, 26
Sea cucumber	-	50	6	14
Benthic meiofauna	-	51	51	50
Sessile epibenthos	-	46	6	14
Mulina coloradensis	5	-	27	5
Bivalves	5	46	27	5

Appendix 11. Continuation.

1950s model	Biomass	P/B	Q/B	Diet
Juv. Blue shrimp	-	-	52	52
Zooplankton	3	14	53	53
Seagrasses	-	54	-	-
Seaweeds	-	54	-	-
Phytoplankton	14	54	-	-
Macroalgae	-	55	-	-
Detritus	6	-	-	-

References cited in appendix 11:

(1) Local fishers Knowledge, 2003 (see chapter III for details). (2) Stock assessment, Virtual Analysis of Population (see chapter III for details). (3) Scripps Institution of Oceanography, 1957. (4) Zeistzchel, 1969. (5) Kowaleski *et al.* 2000. (6) Pauly, 1986. (7) Compagno, 1999. (8) Compagno, 1995. (9) Galván-Magaña & Niehnhuis, 1989. (10) FishBase, 2006. (11) Vidal and Gallardo, 1996. (12) IMMA, 2001. (13) Garcia, 1976. (14) Morales *et al.* 2004. (15) Lluch-Belda, 1970. (16) García-Rodríguez, 1999. (17) Zavala, 1997. (18) D'Agrosa *et al.* 2000. (19) Cetacea, 2001. (20) Ortiz, 1999. (21) Brownell, 1986. (22) Pauly, 1980. (23) Chao, 1995. (24) Smith-Vaniz,1995. (25) Craig, 1960. (26) Arreguín-Sánchez *et al.* 1996. (27) Pauly *et al.* 1993. (28) Dale *et al.*, 1984. (29) Collette, 1995. (30) Collette and Russo, 1984. (31) Collette, 2003. (32) Rojo-Vázquez *et al.*, 1999. (33) Rojas-Herrera and Chiapa-carrera, 2002. (34) Arreguín-Sánchez *et al.*, 2002. (35) Velarde *et al.* 1994. (36) Mellink *et al.* 1997. (37) McEachran, 1995a, b. (38) Hensley, 1995. (39) McKay and Scheiner, 1995. (40) Optiz, 1993. (41) CephBase, 2001. (42) Hendrix, 1985. (43) Crustacean, 2001. (44) Flannagan and Hendrickson, 1976. (45) Vidal *et al.* 1999. (46) Brey, 1999. (47) Velarde et al., 1994. (48) López-Martínez *et al* 1997. (49) Aragón-Noriega, 2000. (50) Chávez *et al.* 1993. (51) Salazar-Vallejo, 1990. (52) Aragón-Noriega and Calderón-Aguilera, 2001. (53) García-Pamanes and Lara-lara, 2001. (54) Meling-López and Ibarra-Obando, 1999. (55) Stewart and Norris, 1981.